INFRARED TESTING OF
ELECTRONIC COMPONENTS

Final Report

Contract No. NAS 8-20131

5 April 1965 through 5 June 1966

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Prepared for

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

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FOREWORD

This final report was prepared for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, by the Orlando Division of the Martin Company, Martin Marietta Corporation in accordance with Exhibit A of Contract NAS 8-20131, dated 5 April 1965.

Prior formal reports under this contract are "Infrared Testing of Electronic Components, Phase I Report," OR 6610, June 1965, and Phase II Report, OR 8031-1, January 1966.

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SUMMARY

A 14-month study program was conducted to explore the feasibility of developing infrared radiation nondestructive test techniques for electrical/ electronic devices. It was recognized at the inception of this program that present assessment techniques were failing to ensure the high degree of quality and reliability required for long range, manned, orbital space missions and similar applications. The overall objective of the program was to detect incipient failures not revealed by present electrical testing methods.

The completed study included three distinct phases of activity: 1) state-of-the-art survey in infrared technology, 2) testing conformal coating materials to standardize surface emissivity, and 3) determining the feasibility of using infrared in various actual applications.

The survey indicated that in a period of less than three years, active interest in applications of infrared technology to electrical/electronic devices had increased in number from two industrial organizations to thirty-two. In a similar trend three government agencies, (MSFC-NASA, RADC, WPAFB), had awarded seven feasibility and development infrared programs to industry. In addition four government agencies (RADC, NASL, NEL, WPAFB) were conducting in-house infrared programs. Problems encountered and areas of infrared development and application were identified. The survey represents an accumulation of information ranging from questionnaires to personal interviews. In addition, literature on infrared developments, pertinent to electrical/electronic applications, was reviewed and abstracted.

In the conformal material testing program, ten finalist coatings were selected and their performance ranked on the basis of 19 test parameters. These materials were tested and ranked to provide a standardized surface emissivity for electrical/electronic components with a high constant value and which met specified mechanical, electrical, and environmental requirements, herein. With the exception of a few relative weaknesses in the areas of adhesion, water absorption, elevated temperature electrical properties, and outgassing, these ten coatings performed satisfactorily as conformal coatings. They were transparent enough to permit component identification and were of extremely high emissivity to permit standardization of infrared measurements.

The final phase of the program tentatively established a relationship between infrared radiation and life expectancy. It appeared that although increased operating temperature did have a deleterious effect on transistor life expectancy, a significant change in temperature must take place before the effect on life can be predicted. Furthermore, indiscriminate scattering of failures in transistors subjected to cyclic electrical overload indicated that besides temperature, other factors, such as design and process variables may have a significant effect on the life expectancy.

Infrared fingerprinting of the operating components on a printed circuit board for thermal derating analysis (determining temperature tolerances) and for troubleshooting was proven to be feasible. Fingerprinting, or thermal profiling techniques, were successfully employed in: 1) locating the hotter components on a printed circuit board, 2) evaluating the effects of relocation (packaging), and 3) accurately evaluating a variety of heat sink configurations and transistor mounting techniques. Not all applications of infrared were successful. For example, the attempt to predict thermal runaway in power transistor applications proved to be unfeasible.

The major conclusion of the study is that the application of infrared technology to test electrical/electronic devices is entirely feasible. Its growth and use requires: 1) selection of appropriate areas of investigation and application 2) development of detailed methodology after exploration of specific applications, and 3) establishment of acceptance criteria based on thermal tolerances and related functions of the electrical-electronic system. Infrared technology will be limited by the economic factor based on relatively high instrumentation costs, development effort required, and high skill necessary to employ the technique.

INTRODUCTION

The purpose of the infrared testing of electronic components contract was to determine the feasibility of developing a nondestructive testing technique, using infrared (IR) radiation measurement, for detecting incipient failures that were not revealed by present electrical testing methods. Contract performance was divided into three phases and covered the period between 5 April 1965 to 5 June 1966.

Phase I involved surveying literature and industry, and government agencies and institutions to determine the state-of-the-art in:

1 IR radiation sensing and measurement instrumentation,

2 IR technology as applied to the nondestructive testing of electrical and electronic components and subsystems,

3 Areas of fabrication and testing presently being investigated for possible application of infrared techniques.

Detailed results were documented in Martin Phase I report, OR 6610 "Infrared Testing of Electronic Components", June 1965.

Phase II consisted of developing one or more conformal coating materials for standardizing the emissivity of electrical and electronic components to a high constant value while meeting specified mechanical, electrical, and environmental requirements. A prime characteristic of the coating was transparency to permit retention of identification of components. Detailed results were documented in the Phase II report, OR 8031-1, January 1966.

The prime objective of Phase III, was to determine the feasibility of further development and applications in the use of infrared technology as a nondestructive testing technique for electrical/electronic parts and subassemblies. Phase III consisted of: 1) establishing a correlation between IR and transistor life expectancy, 2) "fingerprinting" and analysis of circuit designs, 3) investigating use of IR for thermally evaluating packaging techniques, 4) preparation of radiometer and associated equipment procurement specifications.

Results obtained in the Phase III study during the period 8 July 1965 to 5 June 1966 are contained within this final report.

ACKNOWLEDGEMENTS

Industry and Institutions (Cont)

Lockheed Missile and Space Division	Sunnyvale, California
Massachusetts Institute of Technology	Cambridge, Massachusetts
Melpar, Incorporated	Falls Church, Virginia
Motorola, Incorporated	Scottsdale, Arizona
Philco Corporation	Lansdale, Pennsylvania
Pyrotell Corporation	Mamaroneck, New York
Optics Technology, Incorporated	Palo Alto, California
Radio Corporation of America	Somerville, New Jersey
Sylvania Electric	Woburn, Massachusetts
The Raytheon Company	Norwood, Massachusetts
Tektronix, Incorporated	Beaverton, Oregon
Texas Instruments, Incorporated	Dallas, Texas
Thiokol Chemical Corporation	Huntsville, Alabama
Univac Division of Sperry Rand Corporation	St. Paul, Minnesota
Washington State University	Pullman, Washington
Western Electric Company	Allentown, Pennsylvania
Westinghouse Electronic Corporation	Youngwood, Pennsylvania

Government Agencies

Air Force Aero Propulsion Laboratory	Wright-Patterson Air Force Base, Ohio
Air Force Cambridge Research Laboratory	Bedford, Massachusetts
Rome Air Development Center	Griffiss Air Force Base, New York
Electronics Research Center NASA	Cambridge, Massachusetts
Goddard Space Flight Center NASA	Greenbelt, Maryland
Marshall Space Flight Center NASA	Huntsville, Alabama
U.S. Army Engineer Research and Development Laboratories	Fort Belvoir, Virginia
U.S. Army Electronic Laboratory	Fort Monmouth, New Jersey
U.S. Army Missile Command	Redstone Arsenal, Alabama
U.S. Navy Air Development Center	Johnsville, Pennsylvania
U.S. Navy Electronics Laboratory	San Diego, California
U.S. Naval Applied Science Laboratory	Brooklyn, New York
U.S. Naval Ordnance Test Station	China Lake, California
U.S. Naval Weapons Station	Concord, California

I. PHASE I - INDUSTRY/GOVERNMENT SURVEY AND LITERATURE SEARCH

The industry/government survey and literature search was conducted to determine the level of interest and state of the art in: 1) infrared technology as applied to the nondestructive testing of electronic components and subsystems, 2) infrared radiation measurement instrumentation as related to the task, and 3) areas of fabrication and testing under investigation for possible application of infrared techniques. The literature search and survey efforts were conducted concurrently. The survey was divided into inquiries by mailed questionnaires and by personal interviews of selected personnel in organizations active in investigating the applications of infrared. Continuation of the project into Phases II and III, as well as the direction of these phases, depended on the findings of Phase I.

A. QUESTIONNAIRE SURVEY

1. Planning of Questionnaire

Questions for inclusion in the survey were formulated so as to be answered easily and accurately. It was recognized that some form of objective, single answer question would be preferred over the type of question requiring an essay answer. With this in mind, questions were developed which required a minimum of time and effort in answering. Yes-or-no, and multiple-choice item type of question was used predominately. Particular care was taken to avoid the unduly inquisitive question which might induce violations of proprietary or security requirements.

Rather than selecting the list of questionnaire addressees by taking a random sample of all industry and government organizations thought to be capable of conducting infrared programs, the selection was made on a more purposeful basis. That is, a list of organizations known to be interested or involved in infrared measurement programs was generated by reviewing attendance lists of companies represented at various technical symposiums. The most productive sources were the Infrared Techniques for Electronics Committee (ITEC) and the Society for Nondestructive Test (SNT). Another approach which was used to obtain a representative list of questionnaire addressees was one of contacting and requesting equipment user names from leading manufacturers of infrared instrumen-

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tation. This method yielded limited information since the user lists were considered proprietary by the manufacturers and thus not available for this purpose.

Industries, Institutions, and Government Agencies participating in the survey are listed under Acknowledgments.

2. Industry Questionnaire Results

A total of 124 industry survey questionnaires were distributed to 66 organizations known to be interested in the application of infrared techniques to electronic components, subsystems, and systems. Major emphasis of the survey was placed on industrial organizations. However, four universities that had been represented at symposiums of the infrared techniques for electronics committee (ITEC) and/or the Society for Nondestructive Testing (SNT), were included in this group.

Of the 66 organizations contacted, 32 or 49 percent, indicated that infrared techniques for electronics were being explored and/or applied. In addition, four companies indicated that they had two or more distinct IR programs underway at different divisions.

Table I summarizes the major areas where infrared techniques have been or will be applied by these companies. As anticipated from the results of an earlier survey conducted within Martin which indicated that transistors, diodes and resistors were the greatest source of failures in modern electronic systems, these components were receiving special attention relative to infrared testing. These components, of course, are used in circuit board assemblies thus accounting for the emphasis also being placed on circuit boards as shown in Table I.

TABLE I

Application of IR Techniques to Components and Subsystems

Component or Subsystem	Number of Affirmative Replies	Percentage*
Transistors	20	63
Circuit Board Subassemblies	19	59
Resistors	18	56
Integrated Circuits	16	50
Thin Films	14	44
Diodes	13	41
Interconnections	11	34
Multilayer Boards	7	22

* Based on 32 companies and universities indicating that infrared techniques have been explored or applied.

Questionnaire results further indicated that IR measurements have been applied in the areas shown in Table II. Prior articles and papers presented at symposiums have indicated an interest in using IR measurements as a method of selective screening; however, a shifting trend is noted that placed emphasis on electronic design-packaging and failure analysis uses.

TABLE II

Application of IR Techniques to Functional Areas

Area of Activity	Number of Affirmative Replies	Percentage*
Design Packaging of Circuit Boards, Thin Films, or Integrated Circuits	14	44
Failure Analysis/Diagnostic Measurements	11	34
Selective Screening of Components	9	28
Assist in Design of Components	6	19
Process Control of Circuit Boards, Thin Films, or Integrated Circuits	4	13

*Based on 32 companies and universities indicating that IR techniques have been explored or applied.

Table III indicates the techniques employed or which were planned to compensate for emissivity variations encountered in measuring infrared radiation. It is apparent that a special coating of high emissivity was considered by industry as being the most desirable as a compensating means.

TABLE III

Techniques Employed to Compensate for Emissivity Variations

Techniques	Number of Affirmative Replies	Percentage
Specially developed conformal coating of high emissivity	18	56
Standard materials of known emissivity	13	41
Filters	6	19
Dual Optical System	3	10

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Nine companies or 28 percent of those companies who now have IR programs were engaged in the manufacture of infrared radiation measurement equipment; 16 or 50 percent manufacture electronic or electrical components and 27 or 85 percent fabricate or assemble electronic and electrical subsystems and systems.

Both normal and accelerated life testing techniques have been employed to correlate IR radiation with component life. The response showed that 5 companies or 16 percent have used normal testing, while 6 or 19 percent have used accelerated life testing. Twenty-four companies or 75 percent indicated no correlative life testing program.

3. Government Questionnaire Results

The government survey revealed considerable interest in applying infrared test techniques to electronics from 11 agencies responding to the questionnaire. Table IV indicates that the government agencies showed more interest in process controls and failure analysis and less in design analysis techniques.

TABLE IV

Reported Areas of Government Interest and Application

Area of Interest	Number of Affirmative Replies
Component, Subsystem, or System	
Integrated Circuits	5
Resistors	5
Transistors	4
Diodes	4
Circuit Boards	4
Thin Films	3
Interconnections	2
Multilayer Boards	0
Application	
Failure Analysis and Diagnostic Measurements	6
Process Control of Circuit Boards/Thin Films, Integrated Circuits or Multilayer Boards	4
Design and Packaging of Circuit Boards/Thin Films, Integrated Circuits or Multilayer Boards	3
Fault Detection Instrumentation and Systems	3

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TABLE IV (Cont)

Application	Number of Affirmative Replies
Selective Screening of Electronic Components	3
Design of Electronic Components	2
Emissivity Coating Development for Standardizing Infrared Radiation Measurements	2
Infrared Radiation Measurement Instrumentation and System Improvements (Application: Electronic/Electrical)	2

Considerable interest in IR techniques for selective screening of components had been indicated by one of the governmental agencies. As shown in Table V, Rome Air Development Center (RADC) had awarded two contracts for the purpose of determining the feasibility of using IR and/or other nondestructive techniques for selective screening of components. RADC had also awarded two other contracts in the area of reliability testing and prediction techniques where IR and other nondestructive test methods are being evaluated. Other agency awards are tabulated in Table V.

Wright-Patterson Air Force Base had awarded a contract to investigate the possible use of IR measurement for isolating electronic faults in circuit boards.

The National Aeronautics and Space Administration, Manned Space Flight Center at Huntsville had awarded a contract to develop a fast scan infrared microscope. Two other contracts awarded by NASA agencies are titled "Thermal Camera" and "IR Measurements in Real Time," but little is known of the details.

Several in-house IR radiation programs and related emissivity programs as applied to electronic/electrical components, subsystems, and systems were reported by government agencies. These are as follows:

1 U.S. Navy Electronics Laboratory - San Diego, California
   * "A High Speed IR Mapping System for Reliability Assessment of Miniature Electronic Circuits:"
   * Equipment in use: Modified Philco Thermal Plotter

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TABLE V

Contract Awards – Infrared Radiation Measurements, Electronic Components, Subsystems, Instrumentations

Agency and Monitor	Contract No.	Title	Company Awarded Contract	Completion Date
NASA Huntsville Alabama (T. Morris)	NAS-8-20131	Infrared Testing of Electronic Components	Martin-Marietta Corporation Orlando, Florida (D. D. Seltzer)	May 1966
NASA OSSA (J. Miles)	NAS-7-100 Code 186-68-02-20-55	Thermal Camera	Jet Propulsion Laboratory Pasadena, California (D. E. Linderman)	–
NASA Huntsville Alabama (E. Mitchell)	NAS-8-11715	IR Measurements in Real Time	General Electric Ithaca, New York (W. M. Teegarden)	–
Rome Air Development Center, New York (A. Feduccia)	AF 30(602)-3259	Nondestructive Reliability Screening of Semiconductor Diodes	Motorola Phoenix, Arizona (K. Davidson)	May 1965
Rome Air Development Center, New York (A. Feduccia)	AF 30(602)-3452	Reliability Screening Using Infrared	Sylvania Woburn, Massachusetts (Dr. B. Selikson)	October 1965

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TABLE V (Cont)

Agency and Monitor	Contract No.	Title	Company Awarded Contract	Completion Date
Rome Air Development Center, New York (R. C. Hallow)	AF 30(602)-3723	Reliability Testing and Prediction Techniques for Integrated Circuits	Texas Instruments Dallas, Texas (Dr. D. A. Peterman)	November 1966
Rome Air Development Center, New York (R. C. Hallow)	AF 30(602)-3727	Reliability Testing and Prediction Techniques for High Power Silicon Transistors	Texas Instruments Dallas, Texas (Dr. D. A. Peterman)	November 1966
Wright-Patterson AFB, Ohio (R. A. Herman)	AF 33(615)-2430	Investigation of Infrared Radiation for Checkout Application	Raytheon Company Norwood, Massachusetts (Dr. R. Vanzetti)	-
NASA Huntsville Alabama	NAS-8-11604	Fast Scan IR Microscope	Raytheon Company Norwood, Massachusetts (Dr. R. Vanzetti)	-
Wright Patterson AFB, Ohio (A. Prettyman)	AF 33(615)-1952	Long Wavelength Infrared Fiber Optics	Optics Technology, Incorporated Belmont, California	-

2 Rome Air Development Center - Griffiss Air Force Base, New York
   * "IR Analysis of Cermet Resistors"
   * "IR Analysis of Silicon Integrated Circuits"
   * Equipment in use: Barnes 1-81A Radiometer and Philco Thermal Plotter

3 U.S. Naval Weapons Station - Concord, California
   * "Nondestructive Testing of Solder Joints and Electronic Circuit Board Components"
   * Equipment in use: Barnes T 4-IR Camera and Lockheed Model VI Scanning System

4 U.S. Navy Applied Science Laboratory
   * "Emissivity Equalization by Thermosetting Coatings"
   * Equipment in use: Barnes T 4-IR camera.

B. PERSONAL INTERVIEW SURVEY

1. Industry

Supplementing the information from the questionnaire replies were personal interviews with the infrared project task leaders of eight different companies. The companies listed below, all active in investigating uses of infrared, were selected to provide a wide cross section of product orientation, areas of application, and instrumentation employed.

1 Raytheon Company, Norwood, Massachusetts

2 Sylvania Electric, Woburn, Massachusetts

3 IBM, Owego, New York

4 Western Electric Company, Allentown, Pennsylvania

5 Philco Corporation, Lansdale, Pennsylvania

6 The Boeing Company, Michoud, Louisiana

7 Texas Instruments Incorporated, Dallas, Texas

8 General Dynamics/Convair, San Diego, California.

Table VI describes the areas of application being investigated by these eight companies, with design analysis and development of new design techniques again appearing as the major areas of interest.

TABLE VI

Areas of Application Being Investigated

Areas of Application	Number of Companies
Thermal Analysis of Conventional Printed Circuit Board Designs	3
Development of Improved Design Techniques for Thin Films	3
Development of Improved Design and Evaluation Techniques for Integrated Circuits	2
Troubleshooting Defective Printed Circuit Boards	2
Thermal Analysis of Transistors to Improve Reliability	1
Using IR to Replace Life Tests Now Run to Assess the Reliability of Production Run Thin Films	1
Receiving Inspection of Complete Printed Circuit Boards	1
Inspection of Completed, Cased Transistors to Screen Those Having Short Life Expectancy	1
Development of a True Scanning Microradiometer with Significantly Superior Spatial Resolution and Speed	1
Investigating the Use of IR Fibre Optics to Monitor Otherwise Inaccessible Points	1
Developing a Better Understanding of the Significance of IR/Semiconductor Relationships and Determining the Most Beneficial Applications	1

Infrared instrumentation employed in investigations by these eight companies included all known commercially available types suited to applications in electronics, and some developed for specific purposes. All commercial types received considerable criticism, with slow scanning speed, inadequate spatial resolution, long response time, and complex data interpretation heading the list. These are further elaborated in problem areas, section I.B.3. At the same time, however, the critics agreed that many of these problems would be eliminated once instrument companies were able to: 1) determine precisely what the instrument requirements were and 2) had a chance to catch up with the sudden demand for improvements brought on by the increase in programs to investigate infrared techniques for electronics. Table VII lists the instruments in use by the eight companies.

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TABLE VII

Types of Instruments Used in Investigations

Instrument	Number in Use
Philco Microradiometer	5
Barnes Microradiometer	1
Baird Atomic Evaporograph	1
Barnes 8 Inch Radiometer with Camera Scanner	1
Special Servo Corporation System	1
Company Developed Microradiometer	1
Company Developed Single Line Scanner Radiometer	1
Barnes Emissometer	1

Several other points which developed as the interview program progressed were:

1   Emissivity Equalization - Equalization of emissivity to some high value was considered essential to the future of infrared techniques for electronics. The ideal technique would be one using a transparent coating material of high constant emissivity which would also act as a protective conformal coat. Although there was complete agreement that this need existed, there was no evidence of effort to develop such a material. Most groups involved in laboratory experiments were spraying surfaces with flat black paint or other interim coatings.

2   Applications - The majority of the investigators felt that the best application of infrared techniques in the near future would be in developing improved design guidelines and techniques and in evaluating designs for "hot spots" detrimental to reliability.

3   Management Problems - Most groups contacted believed that their programs had been adversely affected by oversimplification of the development of infrared techniques in many talks and articles. From experience, the men actually working at investigations were aware that much diligent effort would yet be required before productive use of infrared techniques could be realized.

4   Confidence - There was a universal attitude of confidence that programs would be successful and that infrared test techniques would play a major role in future design, evaluation, and test of electronics systems.

Detailed summaries for each interview may be found in Appendix C of the Phase I Report, OR 6610.

2. Government

Visits were made to four government installations to review IR activities directed at electronic components and subsystems. These were:

1. Rome Air Development Center (RADC) - Griffiss Air Force Base, Rome, New York (A. Feduccia)

2. Navy Applied Science Laboratory (NASL) - Brooklyn Navy Yard, Brooklyn, New York, (N. Burrowes)

3. Signal Corps Engineering Laboratories (SCEL) - Fort Monmouth, New Jersey (A. Rosenblum, H. Wheeler, D. Beaman)

4. Navy Electronics Laboratory (NEL) - San Diego, California, (R. Fraser)

Other installations visited after completion of Phase I include: 1) Goddard Space Flight Center, NASA - Greenbelt, Maryland; and 2) Electronics Research Center, NASA - Cambridge, Massachusetts, (J. Orner).

In summary IR activities at these installations are:

a. Rome Air Development Center

RADC has awarded four tasks to industry on reliability screening, and, on reliability testing and prediction techniques. All four tasks involve the application of IR measurements. However, two of the tasks include other forms of nondestructive test. The efforts are directed in each task on a specific component, such as diodes, transistors, and integrated circuits.

RADC has also directed several in-house explorations using IR analysis on cermet resistors and silicon integrated circuits. Mr. A. Feduccia of RADC expressed that this survey may assist in assessing the actual effort being directed by government agencies and industries to obtain data, thus permitting an evaluation to be made on infrared applications.

Mr. Feduccia also indicated that the programs are exploratory in nature and that data being accumulated may be able to contribute to the decision as to whether IR may be applied in reliability screening and prediction techniques of components and integrated circuits.

b. Navy Applied Science Laboratory

An in-house study on emissivity coatings had been undertaken by NASL. Fifty coatings were surveyed of which twelve were selected for further study. Resins selected were polyesters, epoxies, silicones, and polyurethanes which solidify at room or moderately high temperatures. The criteria used in the selection included chemical and moisture resistance, dielectric strength, adhesion to surface, ease of application, thermal conductivity, and temperature range. The emissivity indices of the coatings ranged from 0.774 to 0.916. Their effectiveness in equalizing emissivity was demonstrated.

Information from a study by Mr. N. Burrowes of NASL is shown in Tables VIII and IX[1]. This study identifies a number of materials of high emissivity, but with various disadvantages in terms of application and/or characteristics required to withstand environmental conditions. Mr. N. Burrowes indicated further work was necessary.

c. Signal Corps Engineering Laboratories

Interest has been indicated by SCEL in a future program exploiting recent infrared findings. The purpose of this program will be to provide a practical means of employing infrared to improve capabilities in the field of nondestructive testing and to facilitate the detection and isolation of faults in electronic circuitry.

d. Navy Electronics Laboratory

NEL is directing an in-house program to develop a high-speed IR mapping system for reliability assessment of production-run miniature circuits.[2] A large portion of the effort was conducted on thin-film resistors. Reported results by NEL are:

- A system consisting of a cryogenically cooled IR detector, a scanning mechanism, electronic circuitry, and a modified facsimile machine has been developed.

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[1] Emissivity Equalization by Thermosetting Coatings, N. R. Burrowes, U.S. Navy Applied Science Laboratory; Brooklyn Navy Yard, Brooklyn, New York.

[2] A High-Speed Infrared Mapping System for Reliability Assessment of Miniature Electronic Circuits, H. F. Dean and R. M. Fraser, U.S. Navy Electronics Laboratory, San Diego, California.

TABLE VIII

Advantages and Disadvantages of Major Thermosetting Materials

Material	Advantages	Disadvantages
Polyesters	1. Good chemical resistance. 2. Low water absorption. 3. High dielectric strength.	1. Not suitable for high frequency applications. 2. Relatively high shrinkage. 3. Limited temperature range.
Epoxies	1. Outstanding adhesion to clean surfaces. 2. Excellent electrical properties. 3. High mechanical strength. 4. High thermal stability. 5. Good chemical resistance. 6. Low shrinkage.	1. High temperature produced by exothermic reaction. 2. Some epoxies are highly toxic.
Silicones	1. Available in many states including fluids, gels, elastomers, foams. 2. Good ozone resistance. 3. High operating temperatures. 4. Good electrical properties. 5. Relatively high thermal conductivity.	1. Poor adhesive properties. 2. Poor resistance to abrasion. 3. Low tensile strength.
Polyurethanes	1. Strong, tough. 2. High abrasion resistance. 3. High thermal resistance. 4. High surface adhesion.	1. Susceptible to moisture during casting process. 2. Low thermal conductivity.

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TABLE IX

Properties of Coatings

Coating	No. of Components	Main Constituent	Pot Life	Cure*	Operating Temp. °C	Emissivity Index
Columbia Technical Corp. Woodside 77, N.Y.						
Humiseal Type x342(A-B)	2	Polyester	20 min.	Overnight at room temp.	130	0.826
Humiseal Type 1H34	1	Silicone	6 mos.	Room temp. or 1-2 hrs. at 200°C	180	0.876
Humiseal Type 1F18	1	Acrylic	1 yr.	Room temp. or 1 hr. at 130°C	155	0.774
3M Company Electrical Prod. Div., St. Paul 19, Minnesota						
"Scotchcast" Brand Resin No. 8	2	Epoxy	1-2 hrs.	Room temp. or 2 hrs. at 60°C	130	0.896
Ciba Products Co. Fairlawn, N.J.						
Araldite ‡ 488E-32	1	Epoxy	1 yr.	Room temp.	130	0.871
Dow Corning Corp. Electronic Prod. Div., Midland, Michigan						
Sylguard 182	2	Silicone	8 hrs.	Room temp. or 4 hrs. at 65°C	200	0.828
General Electric Silicone Prod. Div. Midland, Michigan						
LTV 602	2	Silicone	2-3 hrs.	Room temp. or 5 hrs. at 65°C	200	0.827
Hysol Corp. Olean, N.Y.						
Hysol PC 12-007(A-B)	2	Epoxy	1-2 hrs.	2 hrs. at 60°C	130	0.916
Hysol PC 15 (A-B)	2	Urethane	2-3 hrs.	10 min. at 52°C	130	0.914
Hysol PC 21 (A-B)	2	Epoxy	1-2 hrs.	2 hrs. at 60°C	130	0.890
Sterling Varnish Company Swickley, Pa.						
Sterling† E 251-33	2	Epoxy	35 min.	2 hrs at room temp.	130	0.860
Sterling† E 252-46	2	Epoxy	2-3 hrs.	Room temp.	130	0.866

* Curing conditions flexible check manufacturers literature

† Found difficult to spray

‡ Dielectric strength not determined

- A thermal map of 1-in.-sq. circuit can be made in a 30 minute period. Mapping resolution is sufficient to display large IR energy level changes occurring in a 0.001 inch square circuit area.

- Present circuitry permits mapping of specimens at environmental temperatures of 60 to 70°C.

NEL further reported the use of silicone grease as an emissivity coating; however, unsatisfactory results were obtained. Currently, NEL is attempting to establish guidelines for a thermal specification for the procurement of integrated circuits.

e. Goddard Space Flight Center

Interest in IR application was indicated by a recent acquisition of a Philco Microradiometer for the purpose of failure investigations of electronic parts. At the time of visit little experience had been gained.

f. Electronics Research Center

The Research Center was recently established and programs for future study were being considered.

3. Problem Areas

Aside from the normal technical obstacles that must be overcome in the development of any technique, several points were raised almost unanimously as problems for which no solution was currently in sight.

a. Scanning a Circuit or Device

With the exception of the Baird Atomic Evaporograph, which used a photograph of an infrared sensitive membrane to cover the field of view, the scanning of an area was a mechanized process requiring from several seconds to minutes to accomplish. Higher speed was desired to obtain data more rapidly and was necessary for analyzing component's or circuit's responses to step function inputs.

b. Spatial Resolution

The best resolution available was on the order of a 1 mil diameter spot. Most groups involved in microcircuit or transistor chip analysis felt that this was marginal since wires with a diameter smaller than 0.001 inch were in use. Resolution improvement for future use was deemed essential.

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c. Data Presentation

Although routine use of IR examination on anything like an assembly line basis is still some distance in the future, some companies were already concerned with the high skill level necessary to obtain and interpret data on a circuit or component. No specific development approach was suggested, but desires leaned toward a television picture type of readout that might be readily superimposed on or otherwise compared with a master.

d. Response Time

Although not generally considered a serious problem at the time, most groups felt that no single type of currently available IR instrumentation combined the qualities of rapid response time, sensitivity, temperature resolution, and range required for investigation of diverse applications.

e. Emissivity Equalization

A need was expressed for a coating material which would provide uniformly high emissivity for all surfaces. None of the companies contacted revealed any effort to develop such a material. It was generally agreed that a material which would serve as a satisfactory emissivity coating would not meet all the requirements of conformal coatings such as the commonly used Hysol compounds. A coating that would not require removal following IR examination, but could be left as a primer for conformal coating would be quite acceptable. In the interim, most companies were going to use laboratory type coatings or standard materials, such as flat black paint, of known emissivity.

f. Administrative Difficulties

Most groups contacted believed that their programs had been adversely affected by purported oversimplification which had been attached to the development of IR techniques in various talks and articles. These groups felt that IR techniques would definitely have an important place in future electronics design. From experience they realize that an extensive and diligent effort would be required for some time in obtaining the necessary data, learning how to interpret it, and putting it to use. One person stated: "It's just like being at the point where we were learning to use X-rays."

C. TECHNICAL REPORT SURVEY

As part of Phase I, reports, magazine articles, and technical papers concerned with the development of IR techniques for electronics were reviewed. Twenty-four reports covering the period from December 1962 to

March 1965 were also reviewed. (See Bibliography, Phase I Report, OR 6610.)

Abstracts of the reviewed articles will be found in Appendix B of Phase I. They were prepared to point up highlights and to avoid tabulated data and technical details. Furthermore, they contain no opinions or conclusions of the abstracter. The report survey indicated that a gradual transition is occurring from the early exploratory probing of a peripheral nature to more specific applications, data accumulation, and detailed descriptions of methodology. This does not mean that any specific areas of application are being dropped by industry as a whole, nor does it mean that all are now looking toward the same few applications. Different groups have simply had time to assess the value of the many potential applications with relationship to their own general fields of endeavor and to select a limited number for more concentrated research. Some typical applications under current investigation are:

1 Selective screening of transistors

2 Development of new design criteria for thin film circuits

3 Selective screening of resistors

4 Development of high speed thermal mapping techniques for micro-electronics

5 Investigation of materials to equalize emissivity.

Several general impressions were left with the reviewer after considering the articles as a collective array of information. These include:

1 Excessive redundancy in describing the fundamentals of infrared theory

2 Great repetition in enumerating the broad potential applications of infrared techniques to electronic components and circuitry

3 Duplication in describing the problem of emissivity

4 Considerable reiteration relative to description of instrumentation, their application, and capabilities

5 Lack of implementation detail concerning conduct of the IR studies

6 Lack of empirical data to substantiate views and opinions expressed.

These impressions are not expressed as criticisms of the authors. Rather, the shortcomings are felt to be a natural consequence of the broad range of possible applications of IR and the newness of the technology at the time the reports were written.

II. PHASE II - HIGH EMISSIVITY CONFORMAL COATING
TEST PROGRAM

A. BACKGROUND

Infrared (IR) energy is radiated by any object whose temperature is above absolute zero. The amount and spectral characteristics of the energy radiated are dependent upon the absolute temperature of the object and also upon the nature of its surface finish or emissivity. Hence, the emissivity factor of an object is a measure of its radiation and absorbing efficiency. Due to the vast number of surface finish variations existing among electronic components, accurate comparison of IR radiation from different components would be a monumental task. Fortunately, emissivity is a surface property, thus it may be possible to achieve a constant emissivity value by coating all surfaces with a uniform film or coating.

The development of one or more coatings, capable of standardizing the emissivity of electronic components to a high constant value under specified electrical, mechanical, and environmental requirements, was the objective of Phase II.

B. TECHNICAL APPROACH

There is an exact relationship between IR emission and absorption which shows that high emissivity requires a material with low reflectance and high absorption. According to Kirchoff's law, absorptivity is directly proportional to emissivity; therefore, a satisfactory absorber is a desirable emitter. It was this relationship that was used during the initial material selection stage of the coating development, to indicate the relative emissivities of the compound being evaluated.

In organic compounds, each generic type of chemical bonding has characteristic absorption frequencies (bands). The number of these absorption bands increases directly with molecular complexity, with band intensity being dependent upon the dipole moment (the difference in the electronegativity between two atoms).

It was initially decided to include for investigation two types of plastic materials having properties meeting the optical, chemical, and physical requirements for emissivity coatings. These were thermosetting plastics,

such as the polyurethanes, silicones, and epoxys, and thermo plastic materials, such as the acrylics and polycarbonates. A coating, previously developed by Martin, which satisfactorily met the transparency and emissivity requirements, was also included in the testing.

C. TESTS

To cover as extensive an area of study as possible, it was planned to review a large number of readily available commercial coating compounds. Those compounds showing potential merit on the basis of vendor data would be selected for screening tests. Those that successfully passed the initial screening tests would then be subjected to further tests to rank them in order of preference for each physical property.

It is realized that there are many more conformal coating type materials commercially available than those included in the test program, and that some of these may have superior characteristics in certain areas. However, within the limitations of the contract it was not possible to evaluate all these compounds at this time.

Results summarized herein are further amplified in the Phase II report, OR 8031-1. In particular photographs of instrumentations and results of tests conducted on additional compounds excluded from this document are included in the Phase II report.

1. Types of Tests

A total of 15 commercially available compounds and 10 Martin prepared compounds were processed through the initial screening tests. Based on the results of these test, which are defined under A1 through A7 in Table X, 10 finalist compounds were selected for the extended tests described under B1 through B11. However, only the 10 finalists have their test results and ratings covered here. Their characteristics as well as those for the eliminated coatings are shown in Table XI.

TABLE X

Types of Tests

Test	Definition (as used in this program)
A. Screening Tests	
1. Viscosity	Resistance to flow resulting from the combined effects of adhesion and cohesion. (Determined on Brookfield Model RVF Viscommeter.
2. Drying Time	The time required for the applied coating to lose its tackiness.
3. Curing Cycle	The time and temperature required for complete cure of the material.
4. Pot Life	The length of time after mixing the constituents of the compound that the material is capable of being applied to printed circuit boards.
5 Infrared Absorption	The relative absorption of IR radiation in the band from about 4 to 14 microns. (Determined by a Beckman IR-9 Spectrophotometer.
6. Transparency	Visual examination of thin films of the materials for their transparency.
7. Emissivity Factor	The efficiency of a radiating surface relative to a perfect black body (1.0 factor).
B. Extended Tests	
1. Maximum Use Temperature	Maximum continuous service temperature.
2. Flexibility	Visual examination of cast sheet material for its general elastic properties.
3. Adhesion	The force required to strip a 1 in. wide length of canvas bonded to an

TABLE X (Cont)

Test	Definition (as used in this program)
	epoxy glass printed circuit board. (Determined in accordance with ASTM-D 903 on an Instron Testing Machine.)
4. Water Absorption	The percent by weight of water absorbed after 24 hours immersion in water at room temperature (per ASTM-D 570).
5. Coefficient of Linear Thermal Expansion	The amount a material changes length with the application of heat. Expressed in inches/inch/degree centigrade. (Determined in accordance with ASTM-D 696 on a Quartz Tube Dilatometer.)
6. Solderability	The ease of repairing a coated soldered joint on a printed circuit board.
7. Chemical Resistance	The effect of various solutions on the coatings.
8. Electrical Properties a Dielectric Strength	Voltage required to break down the insulation resistance of the coating. Expressed in volts per mil. (Performed according to ASTM-D 115 on a Davenport High Potential Tester, Model XVA, 100-50T.)
b Dissipation Factor	The ratio of parallel reactance to the parallel resistance. (Determined at 60 Hertz and performed according to ASTM-D 150 on a General Radio Capacitance Measuring Assembly, Type 1610A.)
c Dielectric Constant	Comparison of the capacitance of a material to that of air, air being

TABLE X (Cont)

Test	Definition (as used in this program)
	assigned a value of 1. (Determined at 60 Hertz and performed according to ASTM-D 150 on a General Radio Capacitance Measuring Assembly, Type 1610A.)
d Surface Resistivity	The resistance to flow of electrical current over the surface of a material. (Expressed in ohms and performed according to ASTM-D 527 on a Freed Megohmmeter Model 1620C and a General Radio Dielectric Sample Holder.)
e Volume Resistivity	The resistance in ohms-centimeter of a substance. (Expressed in ohm-centimeters and performed according to ASTM-D 527 on a Freed Megohmmeter Model 1620C and a General Radio Dielectric Sample Holder.)
9. Outgassing	The percent weight change of a material due to the effect of pressures on the order of 10^{-6} mm Hg.
10. Color Compatibility	The effect of coatings on the appearance of colors. Colors were visually examined through a film of the material.
11. Environmental Tests a Vibration (pre and post test)	The effect of high frequency vibration on electronic components soldered to printed circuit boards.
b High Temperature	The electrical and mechanical effect on a comb resistance pattern etched on a printed circuit board, and on a board with inoperative electronic components, subjected to 250°F for 100 hours.

TABLE X (Cont)

Test	Definition (as used in this program)
c Low Temperature	The electrical and mechanical effect on a comb resistance pattern etched on a printed circuit board, and on a board with inoperative electronic components, subjected to -185°F for 48 hours.
d Temperature Shock	The electrical and mechanical effect on a comb resistance pattern etched on a printed circuit board, and on a board with inoperative electronic components, subjected to cycling between -40°F and +185°F. Test performed similar to methods given in MIL-E-5272.
e Humidity	The electrical and mechanical effect on a comb resistance pattern etched on a printed circuit board, and on a board with inoperative electronic components, subject to high humidity for 10 days. Test performance according to MIL-STD-202, Method 106B.
f Fungus	The extend of life-support engendered to fungus by the coatings during a 28 day exposure. Twenty-six 2 inch squares of sheet epoxy glass coated with the candidate materials served as test specimens. Tests performed in accordance with MIL-E-5272.

TABLE XI

Compounds Screened and Tests Performed

Coating Designation	Type	Viscosity	Drying Time	Curing Cycle	Pot Life	Infrared Absorption	Transparency	Emissivity	Flexibility	Adhesion	Water Absorption	Thermal Expansion	Solderability	Chemical Resistance	Electrical Properties	Outgassing	Color Compatibility	Environmental Tests
1) Products Research PR 1538[1]	Polyurethane	T[3]	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
2) Uralane 5712[1]	Polyurethane	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
3) Humiseal 1A27[1]	Polyurethane	T	T	T	T	T	T	T	T	T	T	NT[8]	T	T	T	T	T	T
4) Humiseal 1A20	Polyurethane	T	T	T	NT[4]	T	T	T	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
5) Minnesota Mining and Manufacturing 3M221	Polyurethane	T	T	T	NT	T	T	T	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
6) Hysol PC 22[1]	Polyurethane	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
7) Hysol PC 15	Polyurethane	T	T	T	NT	T	T	T	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
8) Products Research 1566	Polyurethane	T	T	T	NT	T	T	T	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
9) Magnolia Plastics Magnobond 39[1]	Epoxy-Polysulfide	T	T	T	T	T	T	T	T	T	T	NT[8]	T	T	T	T	T	T
10) Shell Chemical Epon 871 + Epon 828 + Union Carbide L-520 Silicone + M-Phenylenediamine + Catalyst[2]	Epoxy-Silicone	T	T	T	T	T	US[5]	T	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
11) Shell Chemical Epon 871 + Epon 828 + M-Phenylenediamine + Catalyst[2]	Epoxy	NT	T	T	NT	T	US	T	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
12) Shell Chemical Epon 828 + Poly-azelaic Polyanhydride + Benzyl-dimethylamine[2]	Epoxy	NT	T	T	NT	T	T	T	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
13) Union Carbide ERRA 0300 + M-Phenylenediamine + Catalyst[2]	Epoxy	NT	T	T	NT	T	T[6]	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
14) Union Carbide ERLA 0400 + M-Phenylenediamine + Catalyst[2]	Epoxy	NT	T	T	NT	T	T[6]	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
15) Hysol PC 16[1]	Epoxy	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
16) Minnesota Mining and Manufacturing 3M280[1]	Epoxy	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T	T
17) Pyromellitic Dianhydride + M-Phenylenediamine in Dimethyl Acetamide[2]	Polyimide	NT	T	T	NT	T	US	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
18) Amoco Polymer 10[2]	Polyimide	NT	T	T	NT	T	T	T	T	T	T	NT	NT	NT	NT	NT	NT	NT
19) Dupont Polyimide Binder Solution[2]	Polyimide	NT	T	T	NT	T	US	NT	NT	T	NT	NT	NT	NT	NT	NT	NT	NT
20) Martin Emissivity Coating[1,2]	Acrylic	T	T	T	T	T	T	T	T	T	T	NT[8]	T	T	T	T	T	T
21) Humiseal 1B15	Acrylic	T	T	T	NT	T	T	T	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
22) Humiseal 1B12	Acrylic	T	T	T	NT	T	T	T	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
23) General Electric Lexan in Methylene Chloride[2]	Polycarbonate	T	T	T	NT	T	T[7]	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
24) Dow Corning Q92-009[1]	Silicone	T	T	T	T	T	T	T	T	T	T	NT[8]	T	T	T	T	T	T
25) General Electric SS4090[1]	Silicone	T	T	T	T	T	T	T	T	T	T	NT[8]	T	T	T	T	T	T

1 Finalist compound, completely evaluated.
2 Martin preparation.
3 T – Tested
4 NT – Not Tested

5 US – Tested, unsatisfactory
6 Coating cracked
7 Coating peeled, cloudy
8 Not tested due to softness of compound.

2. Screening Tests

a. Viscosity

The viscosity of compounds affects their handling and coating characteristics. Compounds with lower viscosities spray more easily, but have a tendency to coat more thinly when the work piece is suspended on end and allowed to drain. Compounds with higher viscosities produce better fillets, but may be difficult to apply by spraying. Table XII presents the viscosity values obtained at room temperature. The viscosity properties of all compounds were judged to be satisfactory.

TABLE XII

Viscosity of Coatings

Material Designation	Type	Viscosity (Centipoise at 75°F)
Uralane 5712	Polyurethane	9,200
Dow Corning Q92-009	Silicone	9,000
Products Research PR 1538	Polyurethane	8,000
Hysol PC 22	Polyurethane	8,000
Hysol PC 16	Epoxy	7,200
Minnesota Mining and Mfg 3M280	Epoxy	3,800
General Electric SS4090	Silicone	2,400
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	280
Martin Emissivity Coating	Acrylic	150
Humiseal 1A27	Polyurethane	80

b. Drying Time

The drying time was determined by applying thin coatings of the materials on small squares of aluminum and noting the minimum time and temperature required to render the films tack-free. Short drying periods reduce the handling time and are therefore desirable. Some of the compounds required elevated temperatures to promote drying, but this was not felt to be an untenable condition. Drying time and temperature data is presented in Table XIII. All the compounds were satisfactory with respect to drying time.

TABLE XIII

Drying Time

Material Designation	Type	Drying Time/Temp
General Electric SS4090	Silicone	15 min at 75°F
Martin Emissivity Coating	Acrylic	30 min at 75°F
Humiseal 1A27	Polyurethane	30 min at 75°F
Dow Corning Q92-009	Silicone	30 min at 75°F
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	15 min at 170°F
Hysol PC 16	Epoxy	15 min at 170°F
Minnesota Mining and Mfg 3M280	Epoxy	30 min at 170°F
Hysol PC 22	Polyurethane	2 hrs at 175°F
Uralane 5712	Polyurethane	2 hrs at 175°F
Products Research PR 1538	Polyurethane	1 hr at 180°F

c. Curing Cycle

Curing cycles were determined by applying thin coatings of the compounds on small squares of aluminum and noting the minimum time and temperature required to completely cure the coating. Complete cure was indicated by visual appearance, feel, and vendor specifications.

As in the case of drying time, short duration, low temperature cycles are desirable to minimize processing time. However, if a compound had good emissivity and adhesive properties; a longer, higher temperature cycle would not be cause for elimination from consideration. In some usages, a high cure temperature may not be desirable. In these case, greater consideration would be given to the temperature rather than to the time of the cure. The results of curing cycle tests are given in Table XIV. All the compounds were satisfactory with respect to curing cycle.

TABLE XIV

Curing Cycle

Material Designation	Type	Drying Time/Temp
Martin Emissivity Coating	Acrylic	45 min at 130°F
Hysol PC 16	Epoxy	2 hrs at 170°F
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	2 hrs at 170°F
Humiseal 1A27	Polyurethane	50 min at 175°F

Material Designation	Type	Drying Time/Temp
Dow Corning Q92-009	Silicone	60 min at 175°F
Hysol PC 22	Polyurethane	16 hrs at 175°F
Uralane 5712	Polyurethane	16 hrs at 175°F
Products Research PR 1538	Polyurethane	4 hrs at 180°F
Minnesota Mining and Mfg 3M280	Epoxy	2 hrs at 248°F
General Electric SS4090	Silicone	20 min at 265°F

d. Pot Life

Pot life is the work life of a compound, at room temperature, after mixing the components. It is defined as the length of time a coating is capable of being satisfactorily applied to an assembly.

A long pot life is desirable to permit long handling periods of the uncured material. Single component systems, such as Dow Corning Q92-009 and Humiseal 1A27 are easy to work with because they have virtually unlimited pot life and require no weighing or mixing of constituents. Pot life was determined only on the 10 coatings chosen for final extensive testing, as shown in Table XV.

All the compounds were considered to have satisfactory pot life.

TABLE XV

Pot Life of Compounds

Material Designation	Type	Pot Life
Dow Corning Q92-009	Silicone	(1)
Martin Emissivity Coating	Acrylic	(1)
Humiseal 1A27	Polyurethane	(1)
Minnesota Mining and Mfg 3M280	Epoxy	> 1 hour at 75°F
Hysol PC 16	Epoxy	> 1 hour at 75°F
Hysol PC 22	Polyurethane	> 1 hour at 75°F
General Electric SS4090	Silicone	> 1 hour at 75°F
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	> 1 hour at 75°F
Uralane 5712	Polyurethane	> 1 hour at 75°F
Products Research PR 1538	Polyurethane	1 hour at 75°F

(1)One component system with long pot life determined by time material is exposed to air.

e. Infrared Absorption

Infrared absorption was determined on a Beckman IR 9 Spectrophotometer. A film of the liquid coating was applied to a potassium bromide cell and a spectrum was run. Good emissivity was indicated by high absorption through the spectral range.

The prime prerequisite for the desired coating is that it has a high emissivity value. There is a relationship between emission and absorption of radiation that was used in this material study. This relationship shows that a high emissivity material also has low reflectance and high IR absorption. This is stated in Kirchoff's law as: Emissivity = Absorptivity x Constant. IR analysis was therefore used in the screening study to indicate those coating materials which were likely to have a high emissivity. This relationship was used only as a preliminary method of coating evaluation. The final analysis resulted from actual determinations of emissivity values. An examination of the IR versus the emissivity data does not show a readily apparent relationship. Table XVI lists the frequencies at which the ten compounds selected for final evaluation have strong and medium strong absorption bonds. The characteristic general areas of absorption for generic type compounds evaluated in the overall study are also listed.

TABLE XVI

Infrared Absorption Data

Coating Designation	Type	Major Absorption Bands (microns)	
		Strong	Medium
Products Research PR 1538	Polyurethane	4.2 to 4.4, 5.8, 6.5, 6.8, 7.3, 7.7, 8.2, 8.9	10.5, 11.5, 12.1
General Electric SS 4090	Silicone	6.6, 7.8, 9.0, to 10.0, 12.2, 13.8, 14.3	6.2, 6.8
Hysol PC 22	Polyurethane	4.2-4.4, 5.7, 6.4, 8.1, 9.0	6.2, 6.8, 7.2, 10.6
Dow Corning Q92-009	Silicone	7.8, 9.0-10.0, 12.4	4.2, 6.8, 10.9

TABLE XVI (Cont)

Coating Designation	Type	Major Absorption Bands (microns)	
		Strong	Medium
Uralane 5712	Polyurethane	4.3, 4.7, 6.5, 8.0, 9.0	6.2, 7.2, 10.0
Hysol PC 16	Epoxy	6.6, 8.0, 8.4, 9.6, 12.0	5.8, 6.2, 6.8, 8.8, 11.0
Martin Emissivity Coating	Acrylic	5.7, 7.8 to 8.0	7.2, 9.5
Minnesota Mining and Manufacturing 3M280	Epoxy	6.6, 8.0, 9.6, 12.0	6.2, 6.8, 7.7
Humiseal 1A27	Polyurethane	5.7, 6.4, 8.2	4.2, 6.2, 6.8, 9.3, 13.0
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	7.9, 9.5	5.7, 6.2, 6.6, 12.0
Generic Types Acrylics		8-9	7.2
Polyurethane		5.8, 6.5, 8.0, 8.5, 9.0	10.0
Silicones		9-10	6.8
Epoxies		6.6, 8.0, 9.6	6.2, 6.8, 5.9, 6.4, 7.2, 8.0, 9.0
Polycarbonates		5.7, 6.5, 8-9, 9.8, 12.0, 13-14	

f. Transparency

Cured coating films on the order of 5 to 10 mils thick were visually examined to determine transparency. Compounds were considered acceptable if they did not distort or obscure markings used to identify electronic components. As will be noted in Table XVII following, some cloudiness or coloring did exist in several of the compounds; but in each case there was no significant obscuring of identification.

TABLE XVII

Transparency of Cured Coatings

Material Designation	Type	Appearance
General Electric SS4090	Silicone	Clear
Hysol PC 16	Epoxy	Clear
Hysol PC 22	Polyurethane	Clear
Martin Emissivity Coating	Acrylic	Clear
Products Research PR 1538	Polyurethane	Clear
Uralane 5712	Polyurethane	Clear
Dow Corning Q92-009	Silicone	Slightly cloudy, transparent
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	Light amber, transparent
Minnesota Mining and Mfg 3M280	Epoxy	Light amber, transparent
Humiseal 1A27	Polyurethane	Amber, transparent

g. Emissivity

The final screening test to determine the emissivity of the coatings evaluation was made by comparative techniques rather than by absolute measurements of emissivity. The reason for this is that absolute measurement was neither necessary nor advisable in view of the time required to obtain these absolute measurements and that absolute measurements would be made later in the program.

Squares of aluminum, 1.0 x 1.0 x 0.040 inches, were each coated with the material to be evaluated. The squares were then individually placed on a steel platen using Dow Corning DC-4 as the thermal couplant. The temperature of the platen could be controlled better than ±0.1°C. The temperature was raised to 55°C and the infrared output of all coatings compared. Table XVIII shows the relative output levels recorded simply as deflection units of a strip chart recorder. The higher readings have the high emissivity.

3. Extended Tests

The coatings selected as the result of the screening tests were subjected to further tests to rank them in order of their preference for additional physical properties. The following data gives the complete findings of all compounds subjected to the extended tests.

TABLE XVIII

Relative Emissivity Values

Material Designation	Type	Relative Emissivity
Martin Emissivity Coating	Acrylic	25.2
Products Research PR 1538	Polyurethane	25.2
Humiseal 1A27	Polyurethane	25.1
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	25.0
Uralane 5712	Polyurethane	25.0
Hysol PC 22	Polyurethane	24.9
Hysol PC 16	Epoxy	24.3
Dow Corning Q92-009	Silicone	24.1
Minnesota Mining and Mfg 3M280	Epoxy	24.1
General Electric SS4090	Silicone	23.5

a. Maximum Use Temperature

Vendor contact, literature study, and laboratory experience revealed that the maximum continuous use temperature of the majority of coatings under study was approximately 250°F. Whenever applicable, this limitation was observed during all testing. One exception was the elevated temperature electrical properties tests where equipment limitations dictated a maximum temperature of 200°F should be used.

b. Flexibility

The flexibility of a compound affords a measure of the effect of coating expansion on embedded electrical components. This property was evaluated by examining 4 by 4 by 1/8 inch flat sheets of the cured coatings, and rating the compounds "Very Good," "Good," or "Fair." The polyurethanes and silicones all rated as "Very Good," except for Humiseal 1A27 which did not have the elasticity of the others, and was therefore rated as "Good." The epoxies, Hysol PC 16 and Minnesota Mining and Manufacturing 3M280 were classified as "Fair" due to their somewhat rigid structure. Magnobond 39, an epoxy, and Martin Emissivity Cotaing, an acrylic, were somewhat soft at room temperature, but were not as elastic as the polyurethanes. These latter two compounds were rated as "Good" with respect to flexibility. Table XIX lists the compounds and their ratings.

TABLE XIX

Flexibility of Cured Coatings

Material Designation	Type	Rating
Dow Corning Q92-009	Silicone	Very good, rubber like
General Electric SS4090	Silicone	Very good, rubber like
Hysol PC 22	Polyurethane	Very good, rubber like
Products Research PR 1538	Polyurethane	Very good, rubber like
Uralane 5712	Polyurethane	Very good, rubber like
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	Good
Martin Emissivity Coating	Acrylic	Good
Humiseal 1A27	Polyurethane	Good
Hysol PC 16	Epoxy	Fair
Minnesota Mining and Mfg 3M280	Epoxy	Fair

c. Adhesion

The adhesion test was performed in accordance with ASTM-D 903. This consists of bonding a strip of untreated canvas to the material which will be used as a substrate in the final application, in this case an epoxy-glass printed circuit board. The coating compound under test is used as the bonding agent. The canvas is then cut into 1 inch wide strips and peeled in a 180 degree direction from the board, at a speed of 10 inches per minute. An Instron testing machine was used for this operation. The majority of the values listed are the minimum value which could be expected in actual usage, due to the fact that the failure occurred at some interface other than at the printed circuit board surfaces.

Epoxies Hysol PC 16 and Magnobond 39 and urethanes Hysol PC 22, Products Research PR 1538, and Uralane 5712 all displayed very good adhesive quality. In each case, the adhesive testing of these materials resulted in failure of the bond in some place other than at the surface of the printed circuit board. Silicones Dow Corning Q92-009, General Electric SS4090 and the acrylic Martin Emissivity Coating failed at relatively low values, but here too, the failure did not occur at the working surface of the printed circuit board. Minnesota Mining and Manufacturing Company 3M280, and Humiseal 1A27 failed at the board surface, at 5 pounds per inch. Table XX gives the results of the adhesion tests.

TABLE XX

Adhesion of Coatings

Material Designation	Type	Adhesion (lb/in.) and Failure Mode
Hysol PC 16	Epoxy	> 20 canvas broke
Hysol PC 22	Polyurethane	> 20 cohesive failure in resin
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	> 18 adhesive failure at canvas
Products Research PR 1538	Polyurethane	> 15 cohesive failure in resin
Uralane 5712	Polyurethane	> 15 cohesive failure in resin
Dow Corning Q92-009	Silicone	> 6 adhesive failure at canvas
General Electric SS4090	Silicone	> 5 cohesive failure in resin
Martin Emissivity Coating	Acrylic	> 5 cohesive failure in resin
Minnesota Mining and Mfg 3M280	Epoxy	5 adhesive failure at board
Humiseal 1A27	Polyurethane	5 adhesive failure at board

d. Water Absorption

The water absorption tests were performed using a procedure similar to that in ASTM D570. The specimens were conditioned in an oven for 8 hours at 125°F, weighed on an analytical balance, and immersed in water at room temperature for 24 hours. At the end of this soaking period, the specimens were quickly wiped with an absorbent towel, then reweighed on the analytical balance. Water absorption is express in terms of percent of weight change.

General Electric SS4090 silicone showed negligible absorption of water over the test period. Minnesota Mining and Manufacturing 3M280 (epoxy) and Dow Corning Q92-009 (silicone) also had low water absorption values. All but one of the remaining compounds absorbed less than approximately 0.6 percent water. Hysol PC 22, a urethane, absorbed 1.4 percent, a relatively high amount. Table XXI shows the results of the tests.

TABLE XXI

Water Absorption

Material Designation	Type	Percent Water Absorption
General Electric SS4090	Silicone	Negligible
Minnesota Mining and Mfg 3M280	Epoxy	+0.06
Dow Corning Q92-009	Silicone	+0.15
Uralane 5712	Polyurethane	+0.25
Humiseal 1A27	Polyurethane	+0.36
Products Research PR 1538	Polyurethane	+0.37
Magnolia Plastics Magnobond 39	Epoxy-Polysulfide	+0.43
Hysol PC 16	Epoxy	+0.53
Martin Emissivity Coating	Acrylic	+0.58
Hysol PC 22	Polyurethane	+1.40

e. Coefficient of Linear Thermal Expansion (CLTE)

The CLTE was determined in a manner similar to the given in ASTM D696-44. However, this method is not applicable to plastics which will not support the weight of the quartz tube without distortion. Therefore it was not possible to determine the CLTE for all the materials under study. Due to the softness of such materials as General Electric SS4090 and Dow Corning Q92-009, their expansion and contraction would not stress coated components to the extent that would a firmer material of similar expansion. The temperature range between +32° and +80°F was considered to be in the greatest area of interest. Higher temperatures would have unduly softened the materials and led to erroneous results. No great difference in CLTE was noted in the test values. Table XXII shows the results.

f. Solderability

Solderability characteristics were evaluated by determining the ease with which the coatings could be removed from a component solder joint for subsequent removal and replacement of the component. Prior to resoldering, the joint was cleaned with Kester AP20. All of the coatings were found to be readily resolderable, although some displayed a tendency to melt and degrade more than others. This condition requires a more careful cleaning operation of the joint before and after soldering. As shown in Table XXIII, all compounds were considered satisfactory with respect to solderability.

TABLE XXII

Coefficient of Linear Thermal Expansion

Material Designation	Type	CLTE In./In./°F (32°-80°F)
Hysol PC 16	Epoxy	4.76×10^{-5}
Minnesota Mining and Mfg 3M280	Epoxy	5.52×10^{-5}
Uralane 5712	Polyurethane	7.93×10^{-5}
Hysol PC 22	Polyurethane	1.20×10^{-4}
Products Research PR 1538	Polyurethane	1.00×10^{-4}
Dow Corning Q92-009	Silicone	(1)
General Electric SS4090	Silicone	(1)
Magnolia Plastics Magnobond 39	Epoxy Polysulfide	(1)
Martin Emissivity Coating	Acrylic	(1)
Humiseal 1A27	Polyurethane	(1)

(1) material too soft for testing ....could not be made into test configuration

g. Chemical Resistance

Table XXIV gives the effect of various solutions on the thickness, weight, and appearance of the coatings after 4 days immersion at room temperature. The solutions used were as follows:

1 Isopropyl Alcohol - A commonly used cleaner for plastics

2 Methylethyl Ketone - Cleaner solvent used in conjunction with plastics

3 Trichlorethylene - Cleaner solvent used in conjuction with plastics

4 Solder Flux, Kester 1544 - Flux used in solder joints in the printed circuit board area at Martin

5 Flux Remover, Kester AP20 - Used at Martin to clean solder joints

Here as generally would be expected, methylethyl ketone and trichloroethylene had a more severe effect on the coatings tested than did isopropyl alcohol.

TABLE XXIII

Solderability of Coatings

Compound	Type	Solderability Data [1]
General Electric SS4090	Silicone	Coating easily removed. Very little degradation of coating. Resolders well.
Dow Corning Q 92-009	Silicone	Coating easily removed. Joint easily cleaned. Resolders well.
Hysol PC 16	Epoxy	Coating easily removed. Joint easily cleaned. Joint resolders well.
Minnesota Mining and Mfg 3M280	Epoxy	Coating easily removed. Joint easily cleaned. Resolders well.
Hysol PC 22	Polyurethane	Coating melts on heating with iron. Joint must be cleaned well. Joint resolders well.
Uralane 5712	Polyurethane	Coating melts on heating with iron. Must be cleaned well with solvent. Joint resolders well.
Products Research PR1538	Polyurethane	Coating melts on heating with iron. Must be cleaned well with solvent. Joint resolders well.
Martin Emissivity Coating	Acrylic	Coating easily removed but joint must be cleaned well with solvent. Joint resolders well.
Magnolia Plastics Magnobond 39	Epoxy-polysulfide	Coating easily removed. Must be cleaned well with solvent. Joint resolders well.
Humiseal 1A27	Polyurethane	Coating melts on heating with iron. Must be cleaned well with solvent. Joint resolders well.

[1] Coating removed with a hot soldering iron (50 watt). Joint cleaned with Kester AP20 solvent.

TABLE XXIV

Chemical Resistance of Coatings

	Type	Isopropyl Alcohol Thickness Change %	Weight Change %	Methylethyl Ketone Thickness Change %	Weight Change %	Trichloroethylene Thickness Change %	Weight Change %	Solder Flux Kester 1544 Thickness Change %	Weight Change %	Flux Remover Kester AP20 Thickness Change %	Weight Change %
Magnolia Plastics Magnobond 39	Epoxy-Poly-sulfide	+1.1 Good appearance Strong	-1.2	+15.0 Increase in flexibility	+276	+16.2 Bleached Flexible and strong	+75.8	-6.8 Yellowed Flexible and strong	-1.0	-1.4 Good appearance Flexible and strong	+2.4
Dow Corning Q92-009	Silicone	-3.0 Good appearance Flexible and strong	-4.2	+16.4 Flexible and strong	+14.7	+42.9 Flexible and strong	+248	+40.5 Good appearance Flexible and strong	+42.1	+37.4 Curled. Flexible but weakened	+183
Hysol PC22	Poly-urethane	+22.6 Flexible and strong	+59.1	+66.7 Weakened	+243	+72.3 Flexible and strong	+315	+21.5 Yellowed. Weakened	+89.0	+37.3 Flexible and strong	+194
Uralane 5712	Poly-urethane	+9.0 Good appearance Flexible and strong	+13.4	+43.7 Flexible but weakened	+116	+38.7 Flexible and strong	+165	+21.5 Yellowed but strong	+45.0	+20.4 Flexible and strong	+94.2
Hysol PC16	Epoxy	+3.0 Good appearance Strong	+3.0	+6.6 Cracked. Softened.	+15.3	(2) Crumbled	(2)	+2.5 Strong	+3.0	+7.9 Crumbles when bent	+42.5
General Electric SS4090	Silicone	+32.0 Flexible and strong	+43.0	+60.1 Flexible but weakened	+197	+93.8 Grossly swollen. Crumbles	+817	+15.4 Good appearance Flexible and strong	-30.0	+86.9 Grossly swollen. Weak	+810
Minnesota Mining and Manufacturing Company 3M280	Epoxy	+2.5 Good appearance Strong	+5.1	+23.9 Specimen crumbled as it dried	(1)	+23.6 Specimen crumbled	(1)	+1.2 Good appearance Strong	+5.1	+22.0 Specimen crumbled easily	+120
Products Research PR1538	Poly-urethane	+22.0 Swollen, bleached, weakened	+55.6	+46.5 Flexible but weakened	+126	+53.7 Bleached. Weakened	+320	+27.3 Yellowed. Weakened	+112	+39.4 Weakened	+142
Martin Emissivity Coating	Acrylic	(1) Softened within 1 hour	(1)	+35.9 Swollen within 1 hour	+144	(1) Dissolved within 1 hour	(1)	(1) Softened within 1 hour	(1)	+16.2 Curled, no strength	+33.5
Humiseal 1A27	Poly-urethane	(1) Softened within 1 hour	(1)	(1) Dissolved within 1 hour	(1)	(1) Dissolved within 1 hour	(1)	(1) Dissolved within 3 days	(1)	(1) Dissolved within 3 days	(1)

(1) Specimen could not be handled due to crumbling, softening, or dissolution.

The coatings have been listed in descending order of general performance in resisting the solutions. In some cases, special considerations may alter this order of preference considerably. For instance, if ease of removal following measurement of infrared radiation were desired, Humiseal 1A27 or the Martin Emissivity Coating would be most satisfactory.

h. Electrical Properties

The coatings were subjected to tests of 5 electrical properties at room temperature and at 200°F. These were:

1 Dielectric strength

2 Dissipation factor

3 Dielectric constant

4 Surface resistivity

5 Volume resistivity

Since thin coatings tend to give higher dielectric strength values than thicker coatings of the same material, efforts were made to use sheets of uniform thickness for this test. This was not always possible, however, due to the presence of volatiles in some of the coatings.

Humiseal 1A27 softened excessively at 200°F as it was being conditioned for the determination of its electrical properties at elevated temperature. However, the manufacturer states that the material is serviceable at 220°F, and lists electrical properties at this temperature. Therefore, in view of this elevated temperature performance, the polyurethane Humiseal 1A27 and the acrylic Martin Emissivity Coating are rated as having the least satisfactory overall electrical properties of those coatings tested. The results of the tests are shown in Table XXV.

i. Outgassing

For this determination, the ten candidate materials were conditioned at 130°F for eight hours in an oven and then placed in a dessicator for 48 hours. The materials were then removed singly from the dessicator and weighed to the nearest tenth of a milligram on a Mettler Analytical Balance. After weighing, the materials were placed in a vacuum chamber and the pressure reduced to approximately 5.0×10^{-6} mm of mercury. This reduced pressure was held for approximately five hours. At the conclusion of this hold period, the pressure was gradually allowed to return to

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TABLE XXV

Electrical Properties of Coatings

Material Designation	Type		Dielectric Constant (60 Hertz)	Dissipation Factor (60 Hertz)	Surface Resistivity (ohms)	Volume Resistivity (ohm-cm)	Dielectric Strength (volts/mil)	Specimen Thickness (inches)
Dow Corning Q92-009	Silicone	RT[1]	2.94	0.00063	1.30×10^{13}	3.08×10^{14}	674	0.015
		200°F	2.78	0.00048	3.05×10^{12}	2.02×10^{14}	958	0.050
General Electric SS4090	Silicone	RT	2.74	0.00049	1.52×10^{13}	1.40×10^{12}	500	0.045
		200°F	2.54	0.0015	3.05×10^{14}	6.35×10^{12}	395	0.045
3M280[2]	Epoxy	RT	3.34	0.0070	2.34×10^{13}	3.13×10^{13}	405	0.122
		200°F	5.22	0.0051	1.15×10^{13}	2.96×10^{12}	400	0.123
Hysol PC16	Epoxy	RT	4.20	0.016	1.67×10^{13}	1.48×10^{13}	428	0.120
		200°F	9.04	0.141	5.28×10^{11}	3.27×10^{10}	274	0.120
Products Research 1538	Poly-urethane	RT	6.58	0.019	1.27×10^{13}	1.31×10^{12}	309	0.122
		200°F	6.86	0.066	7.37×10^{11}	4.47×10^{10}	493	0.122
Uralane 5712	Poly-urethane	RT	5.15	0.024	2.08×10^{13}	6.51×10^{12}	352	0.122
		200°F	6.10	0.011	5.79×10^{11}	2.42×10^{11}	464	0.123
Hysol PC22	Poly-urethane	RT	6.98	0.029	5.33×10^{12}	2.66×10^{11}	428	0.124
		200°F	7.37	0.042	3.30×10^{11}	1.31×10^{10}	443	0.124
Magnolia Magnobond 39	Epoxy-Poly-sulfide	RT	6.80	0.018	2.80×10^{13}	5.05×10^{12}	1500	0.128 0.08
		200°F	8.0	0.40	6.30×10^{11}	4.04×10^{9}	450	0.128
Humiseal 1A27	Poly-urethane	RT	2.90	0.0026	3.65×10^{12}	1.18×10^{14}	1005	0.022
		220°F[3]	3.7[3]	0.010[3]	6.0×10^{9}[3]	2.00×10^{13}[3]	2400[3]	Not given
Martin Emissivity Coating	Acrylic	RT	2.13	0.065	1.52×10^{13}	1.62×10^{12}	400	0.050
		200°F	[4]	[4]	[4]	[4]	[4]	[4]

(1) Room Temperature (RT)
(2) Minnesota Mining and Manufacturing Company
(3) Vendor Data
(4) Material not serviceable at 200°F

ambient. The samples were then removed, placed into a dessicator, and then singly removed and subsequently reweighed on the Mettler Balance.

Two test specimens represented each coating. The epoxies lost little to no weight. The polyurethanes, for the most part, lost a small amount of weight. The solvent-containing systems, such as General Electric SS4090 and Martin Emissivity Coating suffered the greatest weight loss. One compound, Humiseal 1A27, displayed a slight weight gain of 0.1 percent. This weight gain could possibly be attributable to moisture pickup immediately subsequent to outgassing, during return to ambient pressure. Specimen size was about 1.5 to 2.5 grams in sheet form. Table XXVI shows results of the tests.

TABLE XXVI

Weight Change Caused By Outgassing of Coatings

Material Designation	Type	Weight Change -%
Hysol PC16	Epoxy	Nil
Minnesota Mining and Manufacturing 3M280	Epoxy	Nil
Hysol PC 22	Polyurethane	-0.09
Humiseal 1A27	Polyurethane	+0.10
Magnolia Plastics Magnobond 39	Epoxy-polysulfide	-0.14
Products Research PR1538	Polyurethane	-0.14
Dow Corning Q 92-009	Silicone	-0.51
Uralane 5712	Polyurethane	-0.79
Martin Emissivity Coating	Acrylic	-0.94
General Electric SS4090	Silicone	-5.51

j. Color Compatibility

A color compatibility test was also performed to evaluate the compounds' distortion of standard component color codes. This consisted of painting stripes of the 10 standard colors on a sheet of glass and then viewing them through glass microscope slides coated with the various materials. No masking or alteration of the colors was noted.

3. Environmental Tests

The following environmental tests were performed: 1) Vibration, 2) High Temperature Resistance, 3) Low Temperature Resistance, 4) Temperature Shock, 5) Humidity Resistance, 6) Post Vibration and 7) Fungus. Each of these tests is described in Table XXVII.

TABLE XXVII

Summary of Environmental Test Conditions

Environmental Test	Test Time Duration	Test Condition	Tests Conducted	Applicable Test Specification	Comments
Humidity	10 days	Temperature limit of 149°F	Resistance checked at end of first, third and tenth test day.	MIL-STD-202 Method 106B	No application of power or vibration during test.
High Temperature	100 hours	250°F	Resistance checked every 24 hours, starting at 48 hours. Resistance checked before and after elevated temperature.	Similar to MIL-E-5272	No electrical load applied during temperature application.
Low Temperature	48 hours	-65°F	Resistance checked before and one hour prior to test termination.	Similar to MIL-E-5272	
Temperature Shock	3 cycles of 2 hours	-40°F to +185°F with 5 minute transfer time	Resistance checked before and after environment.	Similar to MIL-E-5272	
Fungus	28 days		Visual examination only.	MIL-E-5272	
Vibration	3 minutes in each of 3 axes	Random vibration envelope equivalent to 38.5g rms	Visual examination before and after environment.	MIL-STD-810 Method 514.1 Random Test Curve J	No application of power during test.

Samples of each type of coating tested were applied to each of three printed circuit boards which had interlocking comb resistance circuits, with separations of about 0.05 inch between positive and negative patterns. (Figure 1). Three other boards consisting of printed circuits with inactive electronic components attached, were also used for each type of coating as uncoated control boards (Figure 2). In addition, two boards for each type of coating tested, were used to perform the fungus test only. These latter boards did not contain any circuits or components.

The order of performing the environmental tests along with the type of sample board used for each is as follows:

<u>1</u> Vibration   Boards with electronic components only (Figure 1)

<u>2</u> High temperature   Comb pattern and component boards (Figures 1 and 2)

<u>3</u> Low temperature   Comb pattern and component boards (Figures 1 and 2)

4	Temperature shock	Comb pattern and component boards (Figures 1 and 2)
5	Humidity	Comb pattern and component boards (Figures 1 and 2)
6	Post Vibration	Boards with electronic components only (Figures 1 and 2)
7	Fungus	Boards with no components or comb pattern

Vibration tests were conducted before and after temperature and humidity testing.

The following board configurations were used as substrates for the coatings during environmental testing.

Configuration 1 - Standard board material, approximately 2 x 2 inches, with a comb pattern for resistance measurement etched on one side as shown in Figure 1

Configuration 2 - Standard board material, solid clad on one side, with components mounted through to cladding and soldered as shown in Figure 2

Configuration 3 - Standard board material, unclad, approximately 2 x 2 inches
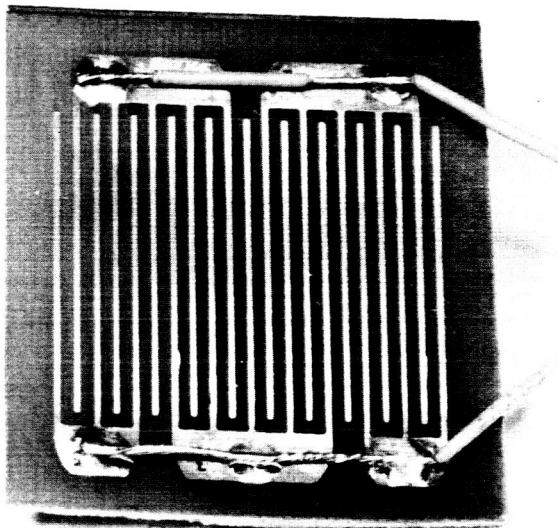
Figure 1. Comb Resistance Circuit Board Used in Environmental Tests

Figure 2. Inactive Com-
ponent Circuit Board
Used in Environ-
mental Tests
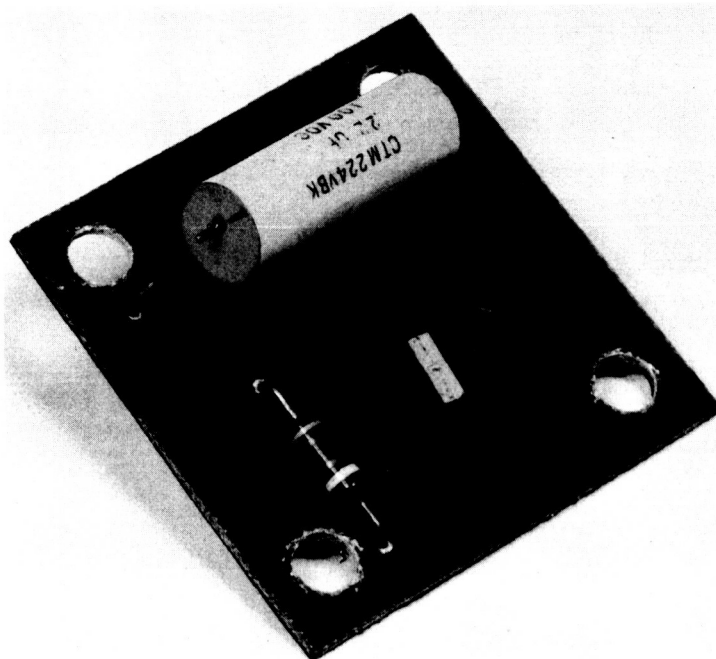
a. Pretest Insulative Values

Insulation readings were taken with a Freed Megohmmeter and 500 volts dc applied to the comb patterns prior to the application of any coating. All values were satisfactory, measuring at least 1×10^{12} ohms. After application of the individual coatings, the resistance readings were rechecked. The values measured, as well as the coating thickness on each board, are listed in Table XXVIII.

b. Vibration

The boards with inactive electronic components were subjected to a random vibration test as follows:

Frequency	Severity
100 cps to 1,000 cps	$1.0g^2$/cps
1,000 cps to 2,000 cps	6 db roll off
50 cps to 100 cps	6 db roll off

The root mean square value of the vibration spectrum was 38.5g. The items were vibrated for 3 minutes in each of the three axis. The boards were subsequently observed to determine if the vibration caused any of the parts to shake loose.

TABLE XXVIII

Resistance After Application of Coatings

Material Designation	Type	Test Board Number	Coating Thickness (Inches)	Resistance (Ohms)
Humiseal 1A27	Poly-urethane	8	0.003	1.5×10^{12}
		9	0.003	1.5×10^{12}
		10	0.002	1.0×10^{12}
Hysol PC16	Epoxy	5	0.003	8.0×10^{11}
		6	0.003	1.0×10^{12}
		7	0.003	1.0×10^{12}
Dow Corning Q92-009	Silicone	11	0.003	7.0×10^{11}
		12	0.004	1.5×10^{12}
		13	0.003	7.0×10^{11}
Magnolia Plastics Magnobond 39	Epoxy-poly-sulfide	14	0.004	3.0×10^{11}
		15	0.004	3.0×10^{11}
		16	0.003	4.0×10^{11}
General Electric SS4090	Silicone	29	0.005	4.0×10^{11}
		30	0.007	3.0×10^{11}
		31	0.007	1.0×10^{11}
Martin Emissivity Coating	Acrylic	20	0.003	3.0×10^{11}
		21	0.003	2.0×10^{11}
		22	0.003	2.4×10^{11}
Uralane 5712	Poly-urethane	17	0.014	2.4×10^{10}
		18	0.015	2.8×10^{10}
		19	0.015	2.2×10^{10}
Hysol PC22	Poly-urethane	2	0.014	1.5×10^{10}
		3	0.013	2.0×10^{10}
		4	0.015	1.0×10^{10}
Products Research PR1538	Poly-urethane	26	0.010	1.4×10^{10}
		27	0.013	1.5×10^{10}
		28	0.015	1.0×10^{10}
Minnesota Mining and Manufacturing 3M280	Epoxy	23	0.003	8.0×10^{11}
		24	0.003	2.0×10^{9}
		25	0.003	8.0×10^{10}
Control		32	none	1.0×10^{12}
		33	none	7.0×10^{11}
		34	none	5.0×10^{11}

This test was performed on the boards before they were subjected to any of the other environments and the test was repeated again after all the other environment tests had been performed.

The first vibration test caused a wire on two of the uncoated control boards to partially open at the solder joint. All coated boards successfully passed without any indication of failure. The second or post environmental test caused the rupture of two wires and the partial failure of a solder joint on the three uncoated control boards. However, no failures were noted on the coated boards. Thus, all coated boards performed satisfactorily during these two tests and gave tangible evidence that the coatings acted as protective mechanisms in preventing physical failure of the solder connections.

c. High Temperature

All boards were subjected to a high temperature test in a hot pack chamber with recorder. Duration of the test was 100 hours at a steady state temperature of 250°F. At the end of 48, 72, and 96 hours respectively, the comb pattern boards were removed one at a time from the chamber and resistance measurements made about 30 seconds after removal from the chamber. Resistance readings appear in Table XXIX.

All coatings showed a decrease in resistance of about one to three orders of magnitude. After being removed from high temperature, the resistances returned to approximately their former values. The performance of the two silicone compounds was superior to that of the other coatings. In general, the epoxies performed next best with the polyurethanes being ranked at the bottom of the list.

d. Low Temperature

All boards were subjected to a low temperature test in a Webber low temperature chamber equipped with a continuous, strip chart recorder. Resistance measurements were made by fastening the comb pattern boards to a piece of plywood and monitoring while the boards were in the low temperature environment. The test duration was 48 hours at a temperature of -65°F. Resistance measurements were noted and appear in Table XXX.

Almost all of the boards showed an increase in resistance at low temperature over that experienced at ambient temperature. However, the low temperature environment had little permanent effect on resistance readings, and all coatings were considered satisfactory for use under comparable conditions.

TABLE XXIX

Effect of Elevated Temperature on Coatings

Material Designation	Type	Test Board No.	Resistance After 48 Hours (ohms)	Remarks	Resistance After 72 Hours (ohms)	Remarks	Resistance After 96 Hours (ohms)	Remarks	Post Hi Temp Resistance (ohms)
GE SS4090	Silicone	29	2.0×10^{10}	No discoloration	2.0×10^{11}	No discoloration	2.2×10^{11}	No discoloration	8.0×10^{11}
		30	3.0×10^{10}	No discoloration	2.0×10^{11}	No discoloration	1.0×10^{11}	No discoloration	1.0×10^{12}
		31	5.0×10^{10}	Slightly discolored	7.0×10^{10}	Slightly discolored	1.6×10^{11}	Slightly discolored	6.0×10^{11}
Martin Emissivity Coating	Acrylic	20	1.6×10^{9}		5.0×10^{10}		5.0×10^{10}		1.0×10^{12}
		21	8.0×10^{8}		3.0×10^{10}		4.0×10^{11}		1.0×10^{12}
		22	8.0×10^{8}		3.0×10^{10}		1.4×10^{10}		9.0×10^{11}
3M280	Epoxy	23	3.0×10^{9}		5.0×10^{10}		7.0×10^{10}		1.5×10^{12}
		24	4.0×10^{8}		5.0×10^{10}		5.0×10^{10}		1.0×10^{12}
		25	6.0×10^{9}		2.0×10^{11}		8.0×10^{10}		9.0×10^{11}
PC Q92-009	Silicone	11	8.0×10^{10}		2.0×10^{11}		1.0×10^{10}		1.0×10^{12}
		12	8.0×10^{10}		3.0×10^{11}		2.0×10^{10}		1.0×10^{12}
		13	5.0×10^{9}		2.0×10^{10}		1.0×10^{10}		1.0×10^{12}
Hysol PC16	Epoxy	5	2.0×10^{10}		2.0×10^{10}		4.0×10^{8}		2.0×10^{12}
		6	4.0×10^{10}		1.0×10^{10}		1.0×10^{10}		2.0×10^{12}
		7	5.0×10^{10}		5.0×10^{9}		1.0×10^{10}		1.0×10^{12}
Magnobond 39	Epoxy-Poly-sulfide	14	4.0×10^{8}		1.0×10^{10}		1.0×10^{9}		2.0×10^{12}
		15	4.5×10^{8}		2.0×10^{11}		7.0×10^{9}		6.0×10^{11}
		16	3.0×10^{8}		3.0×10^{10}		9.0×10^{8}		7.0×10^{11}
Humiseal 1A27	Poly-urethane	8	1.0×10^{11}		1.0×10^{10}		1.0×10^{9}		1.0×10^{12}
		9	8.0×10^{10}		1.0×10^{10}		1.0×10^{10}		1.0×10^{12}
		10	5.0×10^{10}	Slightly discolored	2.0×10^{10}	Slightly discolored	9.0×10^{8}	Slightly discolored	1.0×10^{12}
Products Research PR1538	Poly-urethane	26	1.6×10^{8}	Tacky	7.0×10^{8}	Tacky	2.6×10^{8}	Tacky	4.0×10^{9}
		27	9.0×10^{7}	Tacky	4.5×10^{8}	Tacky	2.4×10^{8}	Tacky	3.4×10^{9}
		28	2.4×10^{8}	Tacky	5.0×10^{8}	Tacky	2.4×10^{8}	Tacky	3.6×10^{9}
Uralane 5712	Poly-urethane	17	1.0×10^{8}	Slightly discolored	9.0×10^{8}	Slightly discolored	4.0×10^{8}	Slightly discolored	1.4×10^{10}
		18	4.0×10^{7}	Slightly discolored	3.0×10^{8}	Slightly discolored	8.0×10^{7}	Slightly discolored	1.6×10^{10}
		19	3.0×10^{7}	Slightly discolored	2.0×10^{8}	Slightly discolored	5.0×10^{7}	Slightly discolored	8.0×10^{9}
Hysol PC22	Poly-urethane	2	4.0×10^{7}	Slightly discolored	4.0×10^{7}	Slightly discolored	3.0×10^{8}	Slightly discolored	1.2×10^{8}
		3	4.0×10^{7}	Slightly discolored	4.0×10^{7}	Slightly discolored	2.0×10^{7}	Slightly discolored	1.4×10^{9}
		4	9.0×10^{7}	Slightly discolored	4.0×10^{7}	Slightly discolored	6.0×10^{7}	Slightly discolored	1.0×10^{9}
Control		32	6.0×10^{10}	Control	1.0×10^{12}	Control	1.0×10^{11}	Control	1.0×10^{12}
		33	5.0×10^{10}	Control	1.0×10^{12}	Control	3.8×10^{11}	Control	1.0×10^{12}
		34	3.0×10^{10}	Control	7.0×10^{11}	Control	9.0×10^{11}	Control	9.0×10^{11}

Note: In the Remarks columns, an arrow extends from the Martin Emissivity Coating rows through the Magnobond 39 rows pointing to "Slightly discolored."

TABLE XXX

Effect of Low Temperature on Coatings

Material Designation	Type	Test Board No.	Pre-Low Temperature Resistance Reading (ohms)	Low Temp (after 48 hrs environment) Resistance Reading (ohms)	Post Low Temperature Resistance Reading (ohms)
Hysol PC16	Epoxy	5	2×10^{12}	1×10^{12} or greater	1.5×10^{12}
		6	2×10^{12}		2×10^{12}
		7	1×10^{12}		2×10^{12}
Dow Corning Q 92-009	Silicone	11	1×10^{12}		1×10^{12}
		12	1×10^{12}		1.5×10^{12}
		13	1×10^{12}		1×10^{12}
Magnobond 39	Epoxy-polysulfide	14	2×10^{12}		1.5×10^{12}
		15	6×10^{11}		1×10^{12}
		16	7×10^{11}		1×10^{12}
Humiseal 1A27	Poly-urethane	8	1×10^{12}		1×10^{12}
		9	1×10^{12}		1×10^{12}
		10	1×10^{12}		1×10^{12}
Martin Emissivity Coating	Acrylic	20	1×10^{12}		1×10^{12}
		21	1×10^{12}		1×10^{12}
		22	9×10^{11}		1×10^{12}
GE SS4090	Silicone	29	8×10^{11}		9×10^{11}
		30	1×10^{12}		2×10^{12}
		31	6×10^{11}		1.5×10^{12}
3M280	Epoxy	23	1.5×10^{12}		1×10^{12}
		24	1×10^{12}		3.5×10^{10}
		25	9×10^{11}		9×10^{11}
Uralane 5712	Poly-urethane	17	1.4×10^{10}		1×10^{10}
		18	1.6×10^{10}		6×10^{9}
		19	8×10^{9}		7×10^{9}
Products Research PR 1538	Poly-urethane	26	4×10^{9}		4.5×10^{9}
		27	3.4×10^{9}		3.6×10^{9}
		28	3.6×10^{9}		3.3×10^{9}
Hysol PC22	Poly-urethane	2	1.2×10^{9}		8×10^{8}
		3	1.4×10^{9}		9×10^{8}
		4	1×10^{9}		7×10^{8}
Control		32	1×10^{12}		1.8×10^{11}
		33	1×10^{12}		8×10^{11}
		34	9×10^{11}	1×10^{12} or greater	1×10^{12}

e. Temperature Shock

The comb pattern boards and the printed circuit boards with inactive components were subjected to a temperature shock test similar to that specified by MIL-E-5272, with the exception that the high temperature limit was 185°F and the low temperature was -40°F. The boards were held at each temperature extreme for one hour with transfers from one temperature to the other being accomplished in less than five minutes. Three cycles of temperature shock were performed. The comb pattern boards were given a resistance check before starting this test and again at the completion, while the boards were at ambient. Results of the tests are shown in Table XXXI.

With the exception of the Hysol PC 22 coated boards number 2, 3, and 4, the temperature shock test appeared to have a negligible effect on the electrical properties of the boards. Some of the coatings developed small bubbles during this temperature cycling. Although these bubbles had no apparent effect on the electrical properties, they are not desirable.

f. Humidity

All of the printed circuit boards were subjected to a ten day humidity test as specified in MIL-STD-202, Method 106B, Figure 106-1, except that no power was applied during the test and the vibration portion was eliminated. Prior to test initiation, a resistance measurement of the comb pattern boards was made under ambient conditions. Near the end of the first, third and tenth test cycle, the boards were removed from the chamber, five at a time. The leads were wiped clean of moisture and resistance measurements made. The printed circuit boards with inactive electronic components were visually inspected at the end of the tenth cycle. Resistance measurement results appear in Table XXXII.

As would normally be expected, a slight general decrease was noted in the test board resistances as a result of exposure to humidity. However, since no significant resistance changes were noted from one type of compound to the other, all compounds listed are considered as possessing equal qualities relative to withstanding the effects of humidity.

g. Fungus

To determine if materials would support fungus, two printed circuit boards for each type of coating material tested were subjected to a 28 day fungus test in accordance with MIL-STD-E5272C. No electrical checks were made before or after test initiation. At the conclusion of the 28 day period, the boards were visually inspected to determine the effects of the

TABLE XXXI

Effect of Temperature Shock on Coatings

Material Designation	Type	Test Board No.	Pre-Temperature Shock Resistance Reading (ohms)	Post Temperature Shock Resistance Reading (ohms)	Remarks
GE SS4090	Silicone	29	9×10^{11}	2×10^{12}	Small bubbles
		30	2×10^{12}	2×10^{12}	
		31	1.5×10^{12}	2×10^{12}	
Hysol PC16	Epoxy	5	1.5×10^{12}	2×10^{12}	Small bubbles under coating
		6	2×10^{12}	2×10^{12}	
		7	2×10^{12}	2×10^{12}	
Magnobond 39	Epoxy-Polysulfide	14	1.5×10^{12}	2×10^{12}	Small bubbles
		15	1×10^{12}	2×10^{12}	
		16	1×10^{12}	2×10^{12}	
Humiseal 1A27	Poly-urethane	8	1×10^{12}	2×10^{12}	
		9	1×10^{12}	2×10^{12}	
		10	1×10^{12}	1.5×10^{12}	
Dow Corning Q 92-009	Silicone	11	1×10^{12}	2×10^{12}	Small bubbles under coating
		12	1.5×10^{12}	2×10^{12}	
		13	1×10^{12}	1.5×10^{12}	
Martin Emissivity Coating	Acrylic	20	1×10^{12}	2×10^{12}	
		21	1×10^{12}	2×10^{12}	
		22	1×10^{12}	1.5×10^{12}	
3M280	Epoxy	23	1×10^{12}	2×10^{12}	
		24	3.5×10^{12}	4.5×10^{10}	
		25	9×10^{11}	2.0×10^{12}	
Uralane 5712	Poly-urethane	17	1×10^{10}	4×10^{10}	Small bubbles Small bubbles
		18	6×10^{9}	4×10^{10}	
		19	7×10^{9}	2.2×10^{10}	
Products Research 1538	Poly-urethane	26	4.5×10^{9}	7×10^{9}	
		27	3.6×10^{9}	5×10^{9}	
		28	3.3×10^{9}	5×10^{9}	
Hysol PC22	Poly-urethane	2	8×10^{8}	1.5×10^{9}	
		3	9×10^{8}	1.8×10^{9}	
		4	7×10^{8}	1×10^{9}	
Control		32	1.8×10^{11}	1×10^{11}	
		33	8×10^{11}	4×10^{11}	
		34	1×10^{12}	2×10^{12}	

TABLE XXXII

Effect of Humidity on Coatings

Material Designation	Type	Test Board No.	Pre-Humidity	End of 1st Cycle	End of 3rd Cycle	End of 10th Cycle
Humiseal 1A27	Poly-urethane	8	7×10^{11}	7×10^{10}	5×10^{10}	8×10^{10}
		9	6×10^{11}	2×10^{11}	8×10^{8}(1)	1×10^{11}
		10	3.2×10^{11}	5×10^{10}	2.1×10^{9}	5×10^{10}
Magnobond 39	Epoxy-polysulfide	14	4×10^{11}	8×10^{10}	4.5×10^{10}	1×10^{11}
		15	5×10^{11}	1.6×10^{11}	4×10^{10}	4×10^{10}
		16	4×10^{11}	1.6×10^{11}	2.8×10^{10}	4×10^{10}
GE SS4090	Silicone	29	5×10^{11}	2×10^{11}	4.5×10^{9}	3×10^{10}
		30	7×10^{11}	2.4×10^{11}	7×10^{9}	1×10^{11}
		31	3×10^{11}	8×10^{10}	1×10^{10}	4×10^{10}
Dow Corning Q92-009	Silicone	11	4×10^{11}	1.8×10^{11}	3.7×10^{10}	8×10^{10}
		12	3×10^{11}	1.2×10^{11}	3.2×10^{10}	7×10^{10}
		13	2×10^{11}	1×10^{11}	7.5×10^{9}	8×10^{10}
Hysol PC16	Epoxy	5	3×10^{11}	1.2×10^{11}	8×10^{9}	6×10^{10}
		6	4×10^{11}	9×10^{10}	4×10^{10}	7×10^{10}
		7	5×10^{11}	1.6×10^{10}	1×10^{11}	7×10^{10}
3M280	Epoxy	23	4×10^{11}	1.2×10^{11}	3.6×10^{10}	7×10^{10}
		24	5×10^{7}	7×10^{7}	2.4×10^{8}	7×10^{9}
		25	1.6×10^{9}	7×10^{8}	3.6×10^{8}	3×10^{9}
Uralane 5712	Poly-urethane	17	3.6×10^{9}	1×10^{9}	1.6×10^{9}	3×10^{8}
		18	3.6×10^{9}	1×10^{9}	2.4×10^{9}	4×10^{8}
		19	3×10^{9}	1×10^{9}	1.8×10^{9}	5×10^{8}
Martin Emissivity Coating	Acrylic	20	4×10^{11}	5×10^{9}	5×10^{9}	6×10^{8}
		21	5×10^{11}	3×10^{9}	7×10^{9}	1.4×10^{9}
		22	4×10^{8}	8×10^{8}	4.5×10^{9}	3×10^{7}
Product Research PR1538	Poly-urethane	26	1×10^{9}	3×10^{8}	8×10^{8}	1×10^{8}
		27	7×10^{8}	2×10^{8}	4×10^{8}	3×10^{7}
		28	8×10^{8}	2.6×10^{8}	6×10^{8}	1×10^{8}
Hysol PC22	Poly-urethane	2	3.6×10^{8}	1.6×10^{8}	4×10^{8}	8×10^{7}
		3	4.5×10^{8}	1.6×10^{8}	4.5×10^{8}	6×10^{7}
		4	3.6×10^{8}	1×10^{8}	3.2×10^{8}	4×10^{7}
Control		32	1.6×10^{9}	2×10^{7}	8×10^{9}	1×10^{10}
		33	5×10^{9}	4×10^{10}	1.8×10^{10}	3×10^{10}
		34	1.6×10^{9}	4×10^{10}	2.8×10^{10}	6×10^{10}

(1) Reading suspected as being in error

test environment. A complete absence of fungus growth on the test boards was apparent. However, the wood support structure as well as the control located in the circular dish show strong indications of fungus support. Of the compounds tested, none presented any evidence relative to the support of fungus.

4. Absolute Emissivity Values

The completion of the environmental test study concluded the test phase relative to the selection of one or more high emissivity conformal coatings suitable for use in electrical/electronic applications. At this stage of the program, seven of the most promising compounds were selected through an evaluation of the previous test results. Subsequently, absolute emissivity values of these coatings was determined. Table XXXIII lists these coatings and the absolute emissivity.

TABLE XXXIII

Absolute Values of Emissivity of Selected Coatings

Material Designation	Type	Black Body Reference Temperatures		
		95°F 35°C	131°F 55°C	167°F 75°C
Hysol PC16	Epoxy	.974	.959	.958
Humiseal 1A27	Polyurethane	.941	.956	.971[1]
Magnobond 39	Epoxy-Polysulfide	.963	.953	.951
DC Q92-009	Silicone	.960	.951	.943
Products Research PR1538	Polyurethane	.969	.947	.942
Uralane 5712	Polyurethane	.958	.942	.936
GE SS4090	Silicone	.944	.900	<.900
Black Body Reference		.990	.990	.990

[1] No readily apparent reason for the reversal of emissivity value with rise in temperature for this coating was noted.

For these emissivity measurements, the coated aluminim squares, previously used for the relative measurements, were placed individually on a platen using Dow Corning DC-4 as a thermal couplant. Then the temperature of the plates was adjusted until the radiation level was equal to that of a calibrated black body at a specific temperature. Since the reference black body as an emissivity between 0.98 and 1.00, a value of 0.99 was assumed in calculating emissivity as follows:

$$w = e \sigma T^4$$

where

    w = total radiant flux per unit area
    e = emissivity factor
    σ = Stefan-Boltzman constant
    T = absolute temperature (°K)

let

    e_1 = emissivity factor of the coating

    e_2 = 0.99 = emissivity factor of the black body

    T_1 = temperature of the platen

    T_2 = temperature of the black body

    w_1 = total radiant flux per unit area of coating

    w_2 = total radiant flux per unit area of black body.

Then $w_1 = w_2$ since the field of view of the radiometer is fixed and the out-puts adjusted to be equal

$$e_1 \sigma T_1^4 = e_2 \sigma T_2^4$$

σ is constant and may be eliminated, e_2 equals 0.99: Thus

$$e_1 = \frac{0.99\, T_2^4}{T_1^4}$$

5. Rating of Coatings

A study of the tables presenting the test data shows that most of the ten final compounds performed satisfactorily as high emissivity transparent conformal coatings. Some of the test results listed in the tables are composed of more than one factor, such as curing cycle data, solderability, chemical resistance, and electrical properties. Therefore interpretation of these results is subject to variance, being dependent on the end performance desired.

The only specific areas of appreciable weakness that were noted were as follows: 1) adhesion – two coatings, Minnesota Mining and Manufacturing 3M280 and Humiseal 1A27, parted from the test board at a relatively low value, failing at the critical coating/circuit board interface; 2) water absorption – one coating, Hysol PC 22, absorbed an appreciable amount of water (1.4 percent); 3) elevated temperature electrical properties – two coatings, Martin emissivity coating and Humiseal 1A27, softened excessively at the 200°F test temperature; 4) outgassing – one coating, General Electric SS4090, a solvent containing system, outgassed to the extent of losing over 5 percent of its weight. However, in actual usage as a conformal coating, a much thinner film of material would be involved than that used in the outgassing test. This would allow a more complete escape of solvent during cure, therefore reducing the outgassing tendencies of the coating.

In Table XXXIV, each of the ten final coating compounds have been ranked according to their performance on each of the properties as determined during the test program. This table provides a ready reference and permits the rapid selection of a coating to be made for use in any one of a number of environments.

TABLE XXXIV

Rating of Most Promising Coatings

Desired Property				Order of Performance					
	1	2	3	4	5	6	7	8	9	10
Emissivity[1]	PC 16	1A27	M-39[3]	Q92-009	PR1538	UR5712[4]	SS4090	3M280 [5]	PC22 [5]	UR5712 [5]
Curing Cycle	MEC	1A27	Q92-009	PC16	M-39	PR1538	SS4090	1A27	PC16	3M280
Flexibility	Q92-009	SS4090	PC22	PR1538	UR5712	M-39	MEC	MEC	3M280	1A27
Adhesion	PC16	PC22	M-39	PR1538	UR5712	Q92-009	SS4090	MEC	MEC	PC22
Water Absorption	SS4090	3M280	Q92-009	UR5712	1A27	PR1538	M-39	PC16	MEC	PC22
Linear Thermal Expansion	PC16	3M280	UR5712	PR1538	PC22	Q92-009[6]	SS4090[6]	M-39[6]	MEC[6]	1A27[6]
Solderability	SS4090	Q92-009	PC16	3M280	PC22	UR5712	PR1538	MEC	M-39	1A27
Chemical Resistance	M-39	Q92-009	PC22	UR5712	PC16	SS4090	3M280	PR1538	MEC	1A27
Electrical Properties										
Dielectric Constant (RT)[7]	MEC	SS4090	1A27	Q92-009	3M280	PC16	PR1538	UR5712	PC22	M-39
(Hi)[8]	SS4090	Q92-009	3M280	UR5712	PR1538	PC22	M-39	PC16	1A27	MEC
Dissipation Factor (RT)	SS4090	Q92-009	1A27	3M280	PC16	M-39	PR1538	UR5712	PC22	MEC
(Hi)	Q92-009	SS4090	3M280	UR5712	PC22	PR1538	PC16	M-39	1A27	MEC
Surface Resistivity (RT)	M-39	3M280	UR5712	PC16	SS4090	MEC	Q92-009	PR1538	PC22	1A27
(Hi)	SS4090	3M280	Q92-009	PR1538	M-39	UR5712	PC16	PC22	1A27	MEC
Volume Resistivity (RT)	Q92-009	1A27	3M280	PC16	UR5712	M-39	MEC	SS4090	PR1538	PC22
(Hi)	Q92-009	SS4090	3M280	UR5712	PR1538	PC16	PC22	M-39	1A27	MEC
Outgassing at 10^{-6} mm Hg	PC16	3M280	PC22	1A27	M-39	PR1538	Q92-009	UR5712	MEC	SS4090
Environmental Tests										
Hi Temperature Resistance	SS4090	MEC	3M280	Q92-009	PC16	M-39	1A27	PR1538	UR5712	PC22
Low Temperature Resistance	PC16	Q92-009	M-39	1A27	MEC	SS4090	3M280	UR5712	PR1538	PC22
Temperature Shock	SS4090	PC16	M-39	1A27	Q92-009	MEC	3M280	UR5712	PR1538	PC22
Humidity Resistance	1A27	M-39	SS4090	Q92-009	PC16	3M280	UR5712	MEC	PR1538	PC22

(1) Absolute, except as noted
(2) Martin Emissivity Coating
(3) Magnobond 39
(4) Uralane 5712

(5) MEC, PC22, 3M280 unranked. For relative emissivity values, (see Table IX)
(6) Expansion not determined. Compounds assigned equal performance
(7) Room temperature
(8) at 200°F

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III. PHASE III - FEASIBILITY OF
INFRARED AS A NONDESTRUCTIVE
TESTING TECHNIQUE

During this phase of the program the use of infrared techniques in several promising areas was investigated. Selection of the areas was based on the Phase I surveys and on previous research at Martin. Major subtasks of Phase III were:

1 Determining the feasibility of correlating infrared radiation and life expectancy of electrical/electronic devices.

2 "Fingerprinting" circuit assemblies to establish the feasibility of using infrared for a) determining temperature tolerances, b) thermal derating analysis, and c) troubleshooting. ("Fingerprinting" is used in this report to mean measuring the thermal profile of a circuit of a component.)

3 Fingerprinting circuit assemblies to determine the feasibility of using infrared in evaluating thermal design in packaging techniques. This task included tests on three elements of packaging: heat sink design, component mounting on heat sinks, and component density on circuit boards.

4 Preparing a specification adequate for the procurement of an infrared radiometer, associated fixtures, and equipment.

This final phase was initiated concurrently with Phase II, and the work conducted in the approximate order of the subtask just listed. All components were coated with the Martin developed emissivity coating.,

A. SUBTASK 1-INFRARED RADIATION/LIFE
EXPECTANCY CORRELATION

Increased operating temperatures or power dissipation in a transistor decreases its life expectancy. The actual amount of degradation is the question that must be answered. Thus, the purpose of this subtask was to: 1) determine the temperature/life relationship through infrared radiation measurement, and 2) determine the effect of large and small increases in operating temperature on life expectancy. With this data, the value of potential uses of infrared testing techniques may be more realistically appraised.

Assuming that a definite relationship would be found, an X-Y graph was planned to present the relationship between operating life expectancy and, power dissipation and temperature. To develop the necessary data, 240 type 2N717 transistors were placed under ON-OFF cycling tests with ON time monitored by an elapsed time meter. The transistors were divided into the four following groups:

1 Those dissipating 100 percent of maximum rated power in free air (96 transistors)

2 Those dissipating 117 percent of maximum rated power in free air (72 transistors)

3 Those dissipating 134 percent of maximum rated power in free air (48 transistors)

4 Those dissipating 150 percent of maximum rated power in free air (24 transistors)

The 2N717 transistors were selected as best for this investigation because of their case size, power rating, breakdown voltage, internal configuration, and cost. The power levels were established after tests showed that 175 percent of maximum rated power would produce virtually instantaneous catastrophic failure. The total ON-OFF cycle was set at 15 minutes, as a result of previous tests at Martin which showed that temperature stabilization of TO-5 cased transistors occurred approximately 6 minutes after the application or removal of power. Circuit operation was made as simple as possible by using ±1 percent wirewound resistors and well regulated power supplies to assure stability of operation. The circuit for each transistor is shown in Figure 3; voltages and resistance values for the different power levels are listed in Table XXXV.

TABLE XXXV

Life Test Voltage and Resistance Values

Rated Power (Percent)	R1, R2, R3 (ohms)	V_{CC}	V_{BB}
100	750	40.1	20.0
117	560	36.1	20.0
134	450	34.0	20.0
150	375	32.6	20.0
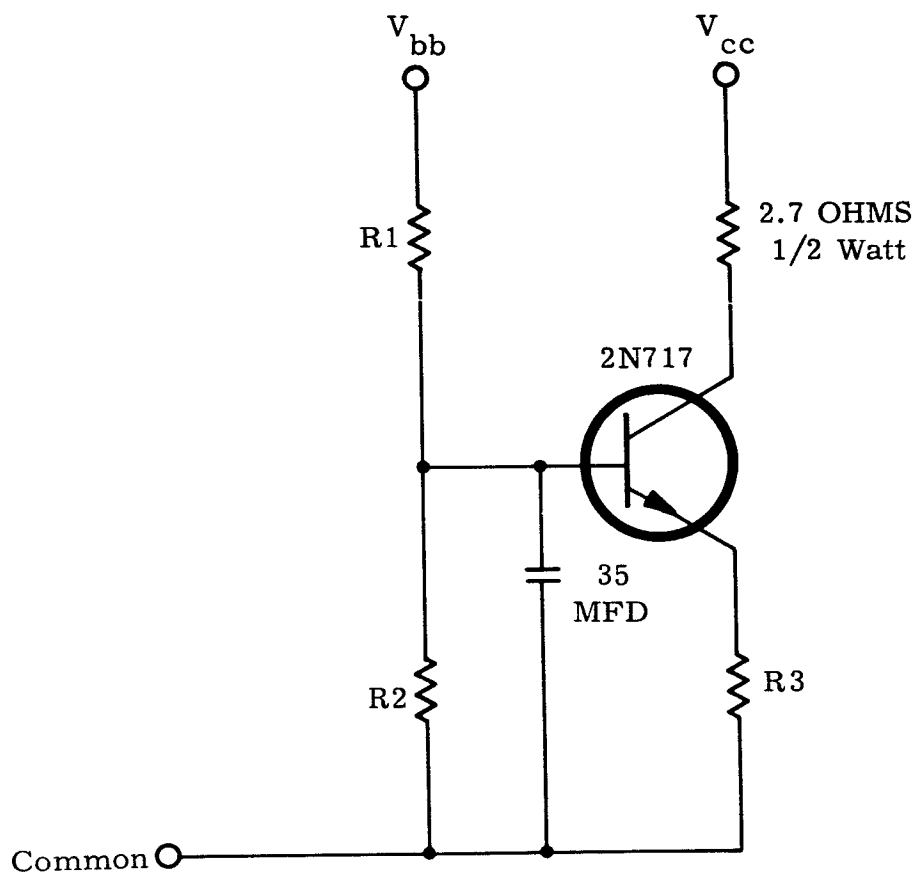
Figure 3. 2N717 Life Test Circuit

Fail-safe circuits were designed and incorporated in the test circuit to protect against power supply failures. These devices automatically remove all power from the transistors under test if supply voltages increase or decrease, or if current drain becomes excessive. Figure 4 is a photograph of the complete infrared life test set-up.

Prior to test, each transistor was identified and numbered and the following parameters were measured:

1   I_{CBO} Leakage

2   BV_{CBO} Breakdown voltage, collector to base

3   BV_{EBO} Breakdown voltage, base to emitter

4   $V_{CE(SAT)}$ Saturation voltage, collector to emitter
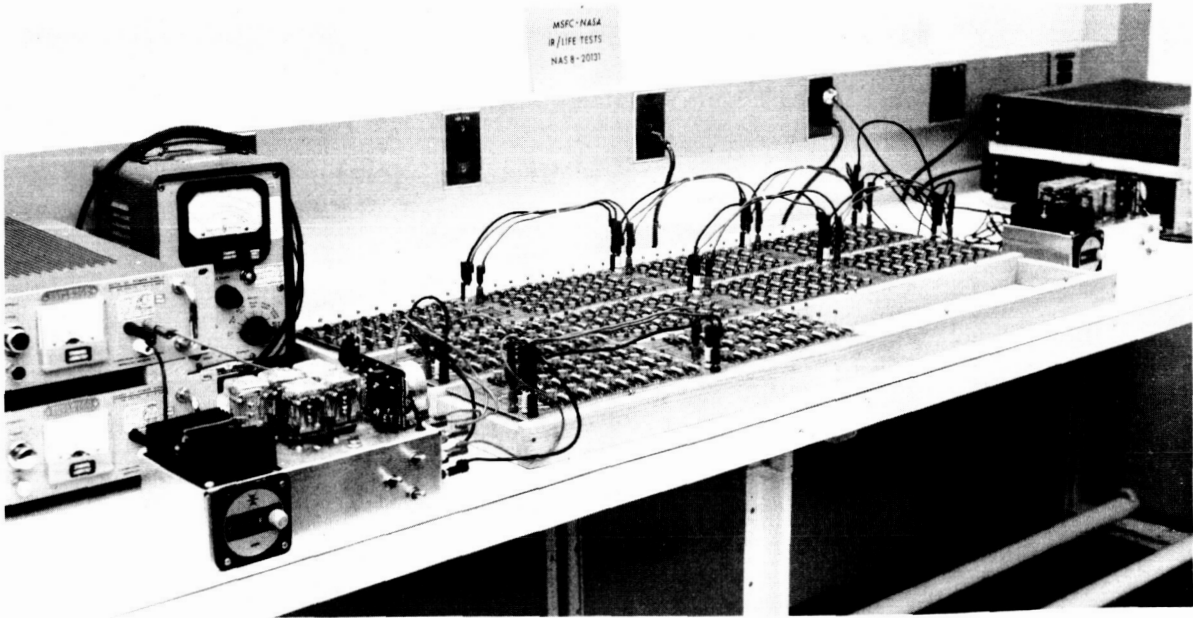
Figure 4. Infrared Life Test Set Up

<u>5</u> $V_{BE(SAT)}$ Saturation voltage, base to emitter

<u>6</u> h_{FE} Gain

<u>7</u> IR   Infrared radiation at the power level to which the
                         component would be subjected

A special computer program was designed to obtain a normal Gaussian
distribution of the infrared data for each power level. This program re-
sulted in the population distribution versus temperature plots shown in
Figure 5. All electrical test results were compiled in a logbook so that
trends in electrical parameters could be detected as testing progressed.
Electrical parameters were retested periodically according to the following
schedule.

<u>1</u> 150 percent   every week   — 84 hours of ON-TIME

<u>2</u> 134 percent   every 2 weeks — 168 hours of ON-TIME

<u>3</u> 117 percent   every 3 weeks — 252 hours of ON-TIME

<u>4</u> 100 percent   every 6 weeks — 504 hours of ON-TIME

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Failure Number	On-time Hours of Test	Cause
F 1	280	Leakage
F 2	280	Shorted
F 3	280	Leakage
F 4	528	Shorted
F 5	528	Shorted
F 6	596	Shorted

*Rated Electrical Load

100 Percent* 117 Percent* 134 Percent* 150 Percent*

Population
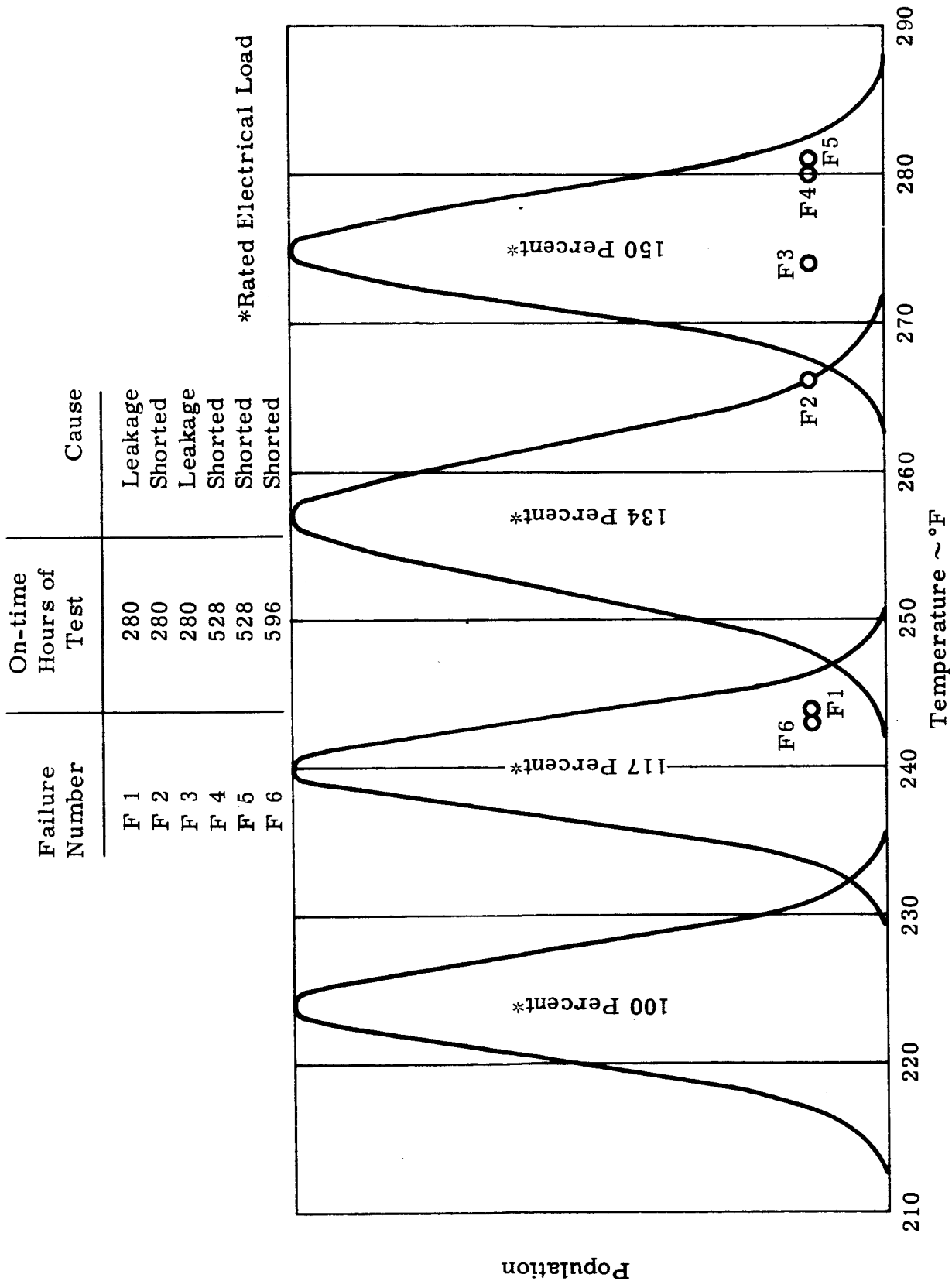
Temperature ~ °F

Figure 5. Temperature Distribution in Infrared Life Test

Any parameter falling outside of the transistor specification limits was considered a failure. At the close of this program, with 1652 hours of ON-TIME accumulated, there have been 6 failures. These failures have been identified in Figure 5 and are within the Gaussian distribution based on the temperature measured for each transistor at the time it was originally acquired. The time of failure detection and cause for removal from test are shown in Table XXXVI.

TABLE XXXVI

Transistor Failures Resulting from Accelerated Life Tests

No. of Transistors Under Test	Percent Power Level	Temperature Range (°F)	Tested at Hours "ON" Time*	Failures
96	100	215-233	0	0
72	117	232-248	0	0
48	134	246-266	0	0
24	150	266-285	0	0
96	100	215-233	100	0
72	117	232-248	100	0
48	134	246-266	100	0
24	150	266-285	100	0
96	100	215-233	200	0
72	117	232-248	200	0
48	134	246-266	200	0
24	150	266-285	200	0
96	100	215-233	300	0
72	117	232-248	300	1 leakage
48	134	246-266	300	1 leakage
24	150	266-285	300	1 shorted
96	100	215-233	400	0
72	117	232-248	400	0
48	134	246-266	400	0
24	150	266-285	400	0
96	100	215-233	500	0
72	117	232-248	500	0
48	134	246-266	500	0
24	150	266-285	500	2 shorted

TABLE XXXVI (Cont)

No. of Transistors Under Test	Percent Power Level	Temperature Range (°F)	Tested at Hours "ON" Time*	Failures
96	100	215-233	600	0
72	117	232-248	600	1 shorted
48	134	246-266	600	0
24	150	266-285	600	0
96	100	215-233	No other failures	
72	117	232-248	to 1650 hours	
48	134	246-266	(end of contract)	
24	150	266-285		

*Test time rounded to nearest 100 hours for this table

B. SUBTASK 2 - THERMAL DERATING ANALYSIS AND TROUBLESHOOTING

In this subtask, thermal profiles or fingerprints of operating circuit boards were made to determine the feasibility of evaluating a design for adequate thermal derating, and to determine the feasibility of using these fingerprints in troubleshooting defective production units.

Six identical Apollo control signal processor rate switch boards, one of which is shown in Figure 6, were used for these tests because: 1) they provided the circuit repetition necessary to establish a standard thermal pattern, 2) they provided relatively high component density so that a large number of components were available on a few boards, 3) the infrared radiation from each component could be readily measured, and 4) they are typical boards designed for actual applications and were not made especially for investigating infrared techniques. The physical layout of these boards is shown in Figure 7. The circuit diagram is shown in Figure 8 and the total bill of materials for all 6 boards in Table XXXVII.

The circuit diagram is only for one circuit, while actually there are 3 identical circuits on each of the six boards. Also, the components on the test boards are not the high-spec, highly reliable types used on the production Apollo units, but conventional equivalents of these units. Use of the special components would have been too expensive for the feasibility investigation.
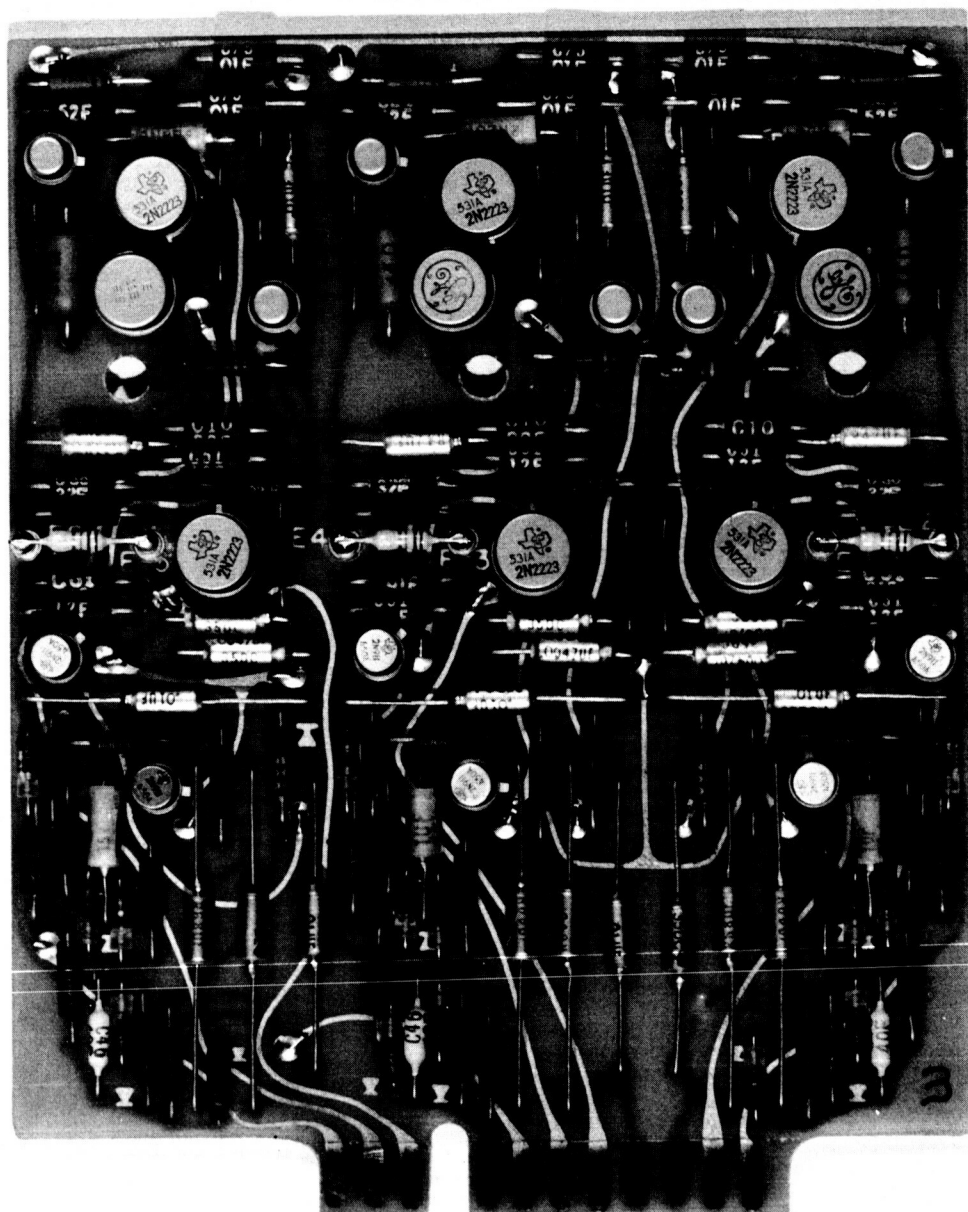
Figure 6. Apollo Rate Switch Board with 3 Circuits
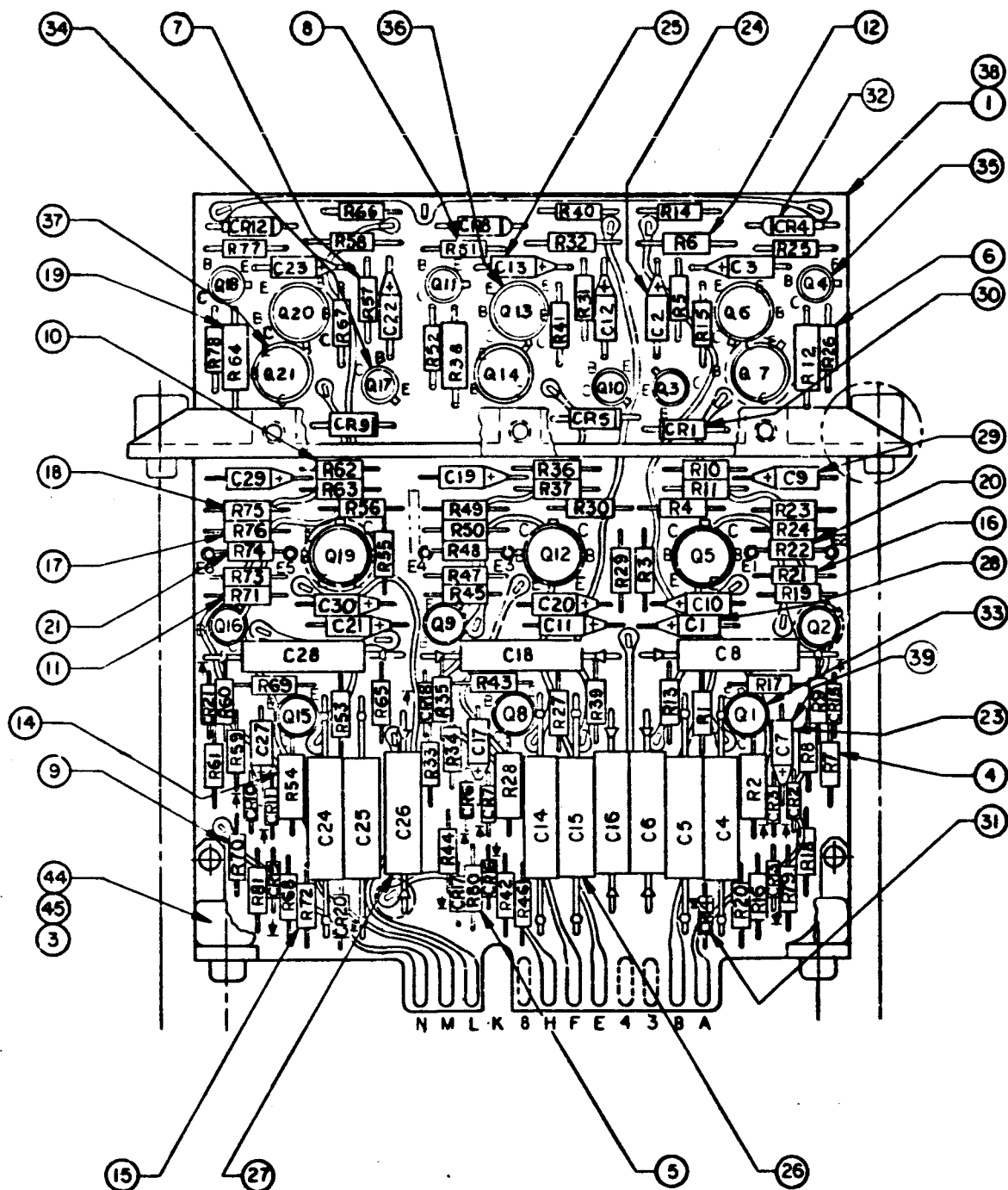
Figure 7. Physical Layout of Apollo Rate Switch Circuit

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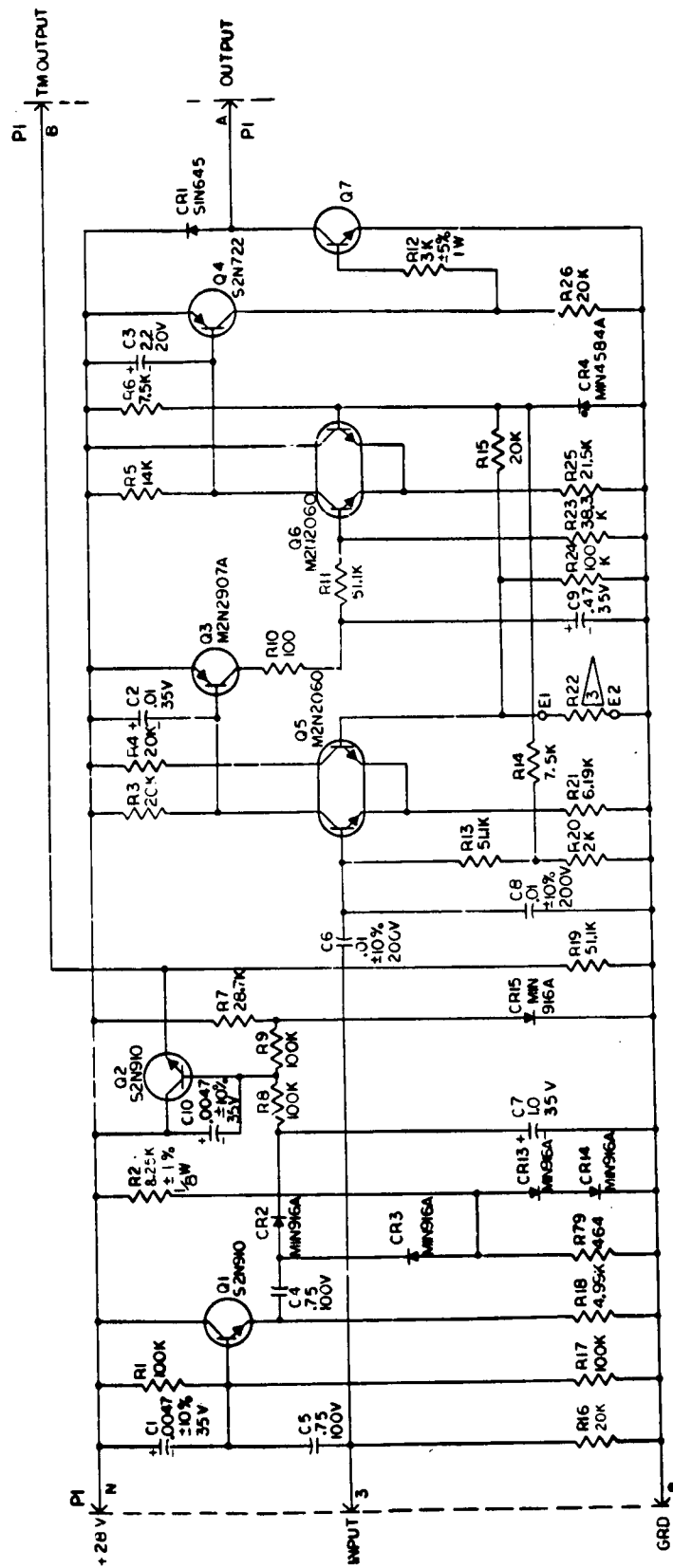
Figure 8. Circuit Diagram of Apollo Rate Switch Circuit

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TABLE XXXVII

Total Bill of Materials, Six Apollo Rate Switch Boards

Find No.	Circuit Components	No. of Components Required	Description
4	R7, 33, 61	18	Res, 28.7K, 1%, 1/10W
5	R79, 80, 81	18	464Ω
6	R3, 4, 15, 16, 26, 29, 30, 41, 42, 52, 55, 56, 67, 68, 78	90	20K
7	R5, 31, 57	18	14K
8	R25, 51, 77	18	21.5K
9	R18, 44, 70	18	4.99K
10	R10, 36, 62	18	100Ω
11	R11, 13, 19, 37, 39, 45, 63, 65, 71	54	51.1K
12	R6, 14, 32, 40, 58, 66	36	7.5K
14	R2, 28, 54	18	8.25K
15	R20, 46, 72	18	2K
16	R21, 47, 73	18	6.19K
17	R1, 8, 9, 17, 24, 27, 34, 35, 43, 50, 53, 59, 60, 69, 76	90	100K
18	R23, 49, 75	18	38.3K, 1%, 1/10W
19	R12, 38, 64	18	3K, 5%, 1W
20	R22, 48, 74	1/ckt	Res, * 1%, 1/10W
30	CR1, 5, 9	18	Diode, IN645
31	CR2, 3, 6, 7, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21	90	Diode, IN908
32	CR4, 8, 12	18	Diode, IN753A
33	Q1, 2, 8, 9, 15, 16	36	Transistor 2N911
34	Q3, 10, 17	18	Transistor 2N2907A
35	Q4, 11, 18	18	Transistor 2N722
36	Q5, 6, 12, 13, 19, 20	36	Transistor 2N2223
37	Q7, 14, 21	18	Transistor 2N1893

*Selective values determined on assembly

1. Component Derating Evaluation - Infrared Radiation Levels

   To evaluate derating of components using infrared radiation levels, the maximum allowable case temperature, or infrared radiation level for each component was initially measured as the components were subjected to the maximum specified electrical power input. Most component specifications,

and those of transistors in particular, provide a rating for maximum power dissipation in free air at an ambient temperature of 77°F (25°C). This rating indicates the power dissipation which will heat the transistor junction to just less than its maximum allowable operating temperature. The heating of the case is merely an outward manifestation of internal junction heating.

The basic steps in determining the maximum allowable case temperature infrared radiation level for each component were:

1. Coating each component with an emissivity equalizer for which the radiometer readout is calibrated directly in temperature

2. Mounting each component so that it is free of any contact which might act as a heat sink except for the leads.

3. Measuring each component's case temperature while the input power is held to the maximum specified rating for free air

4. Evaluating the data to determine the mean value and tolerance of component case temperature

The tolerance, or range of operating temperatures, in these tests was found to be quite narrow. The 2N717 transistors used in the life tests described previously are typical, and in this study provide the best illustration because they form the largest sample size for analytical study. Maximum rated power dissipation of these transistors produced a distribution of case temperatures with a mean of 224°F (107°C) and 3 sigma points of ±11°F (±6°C). In this program, the tolerance of 11°F at maximum case temperature was considered insignificant since in the subsequent study, the Apollo circuit boards were derated and the temperature safety factor was significantly greater than the tolerance.

Precautions taken during measurement were: 1) avoiding drafts across the test pieces, 2) assuring that the radiometer field of view was filled by the surface measured, and 3) selecting the proper physical point for measurement. On a transistor, for example, any point on the top of its case was found to have the same temperature. However, glass cased diodes, such as the IN908's, have a considerable temperature gradient along the length of their envelope due to the variable position of the junction. In such cases, the hottest spot was always used for measurement.

After establishing the maximum temperatures and tolerances of the individual components at maximum power input as rated by specification, the temperatures of the components were measured while functioning normally

on their printed circuit board. There are many situations where power dissipation can fluctuate considerably, such as, in ON/OFF applications. Therefore, the circuit operation should be evaluated under conditions resulting in the highest dissipation while functioning electrically as prescribed in the drawing specification. The physical layout of Figure 7 was used to plot a logical course across each circuit to obtain infrared radiation measurements. The board was indexed so that each component's temperature was measured individually in the prescribed sequence. Capacitor case temperatures are not included in the data because they generate no heat within themselves unless leaky, and temperatures were found to be scarcely above ambient.

After obtaining this data, the design safety factor for elevated ambient temperature was determined as follows:

Maximum anticipated ambient temperature	*167°F	75°C
-Measured ambient temperature	77°F	25°C
Maximum anticipated temperature rise	90°F	50°C
Maximum allowable case temperature from infrared	229°F	109°C
-Actual operating case temperature	102°F	39°C
Maximum allowable case (or ambient) rise	127°F	70°C

Based on this calculation the designer has adequately derated Q4 because the maximum anticipated temperature rise is less than the maximum allowable rise. The safety factor in this case is 37°F (20°C).

In practice, this evaluation can be more simply made by scaling the strip chart recording itself. Referring to Figure 9, where maximum allowable and actual operating case temperatures are plotted; a separate strip of paper cut to scale and representing the maximum anticipated temperature rise can be placed between the actual operating temperature and maximum allowable case temperature for each component. If the scale length does not exceed the difference between the plotted levels, the design is safely derated.

In this report, all strip chart recordings have been faithfully redrawn for clarity of line and conservation of space. Furthermore, component designations are limited to a single number representing all three identical

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*A temperature of 167°F (75°C) was assumed for these tests. This rating is normally obtained from the environmental specification of the circuit.
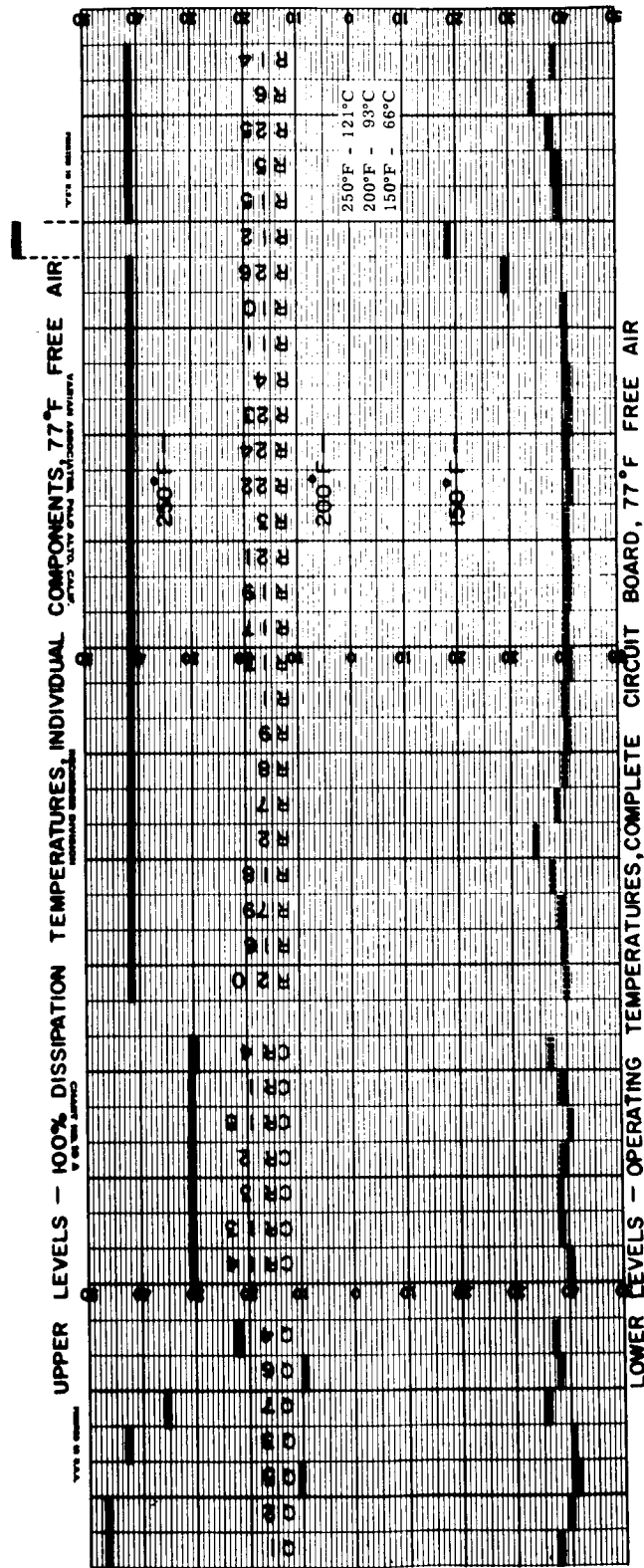
Figure 9. Maximum Allowable and Actual Operating Case Temperatures
for Apollo Rate Switch Board

circuits on each board. For example: the designation Q4 represents the temperature of transistor Q4 on the first circuit on board one, Q11 the second circuit on board one, and Q18 the third circuit on board one.

An error exists in this technique, however, which will restrict its applications; even though it is a "safe" error. This error may be explained by the standard thermal equation for transistors:

$$T_J = P_D \theta_{JC} + P_D \theta_{CA} + T_A$$

where

T_J is the junction temperature of a transistor in °C,

P_D is the power dissipation of the transistor in watts,

θ_{JC} is the junction to case thermal resistance of the particular transistor in °C/watt,

θ_{CA} is the case to ambient thermal resistance of the particular transistor in °C/watt and

T_A is the ambient air temperature in °C where cooling is by normal convection.

From the equation it is apparent that as ambient increases by 1 degree, the junction increased by 1 degree and the case increased by 1 degree. Thus far, the evaluation just described is quite valid. However, when the equation is rewritten in terms of case temperature instead of ambient temperature, it becomes:

$$T_J = P_D \theta_{JC} + T_C$$

where

T_C is the case temperature in °C.

Since θ_{JC} is a constant for the particular transistor, the junction to case differential must become greater with increased power at maximum power dissipation.

As stated previously, case temperature rise is merely an outward indication of inner junction heating. In the evaluation just described, case

temperature was used as a convenient, if not precisely accurate, measure of junction temperature. The fallacy occurs as a result of the equation term $P_D\theta_{JC}$. In the case of a 2N722 transistor dissipating 0.4 watts (maximum rated power in free 77°F ambient), the term shows a junction to case differential of 72°F (40°C). In actual circuit operation, however, the transistor may be dissipating only 0.040 watts with the differential reduced to 7.2°F (4.0°C). Thus the evaluation technique using infrared data alone provided an assessment of derating that was "safe" by 68.4°F (36°C) above the originally calculated 37°F (20°C).

2. Component Derating Evaluation - Infrared Levels and Free Air Dissipation Curves

For practical purposes, the errors occurring in component derating described previously, may be too great. However, they can be largely eliminated through the additional use of plotted curves for junction and case temperature rise occurring with increased dissipation in free air. The transistor 2N722 will again be used as an example to illustrate the method for component derating evaluation.

In Figure 10, the T_J curve shows the rise in junction temperature with increased power dissipation in a free air environment at room temperature. It is merely a straight line between two points: room ambient at zero power dissipation and specification values for maximum operating junction temperature/maximum allowable free air power dissipation. The T_C curve in the figure is derived from the actual infrared temperature measurements and shows the rise in case temperature with increased power dissipation in a free air environment at room temperature. It is a straight line between room ambient at zero power dissipation and the measured case temperature at maximum power as stipulated by specification for a specific component.

To evaluate the derating of component Q4, a 2N722 transistor, the actual operating temperature of the component was obtained by infrared measurement while the unit was functioning in the specified circuit. From the data presented in Figure 10, the junction temperature at this point was 20°F (11°C) above the case temperature. The method of derating the component is as follows:

Maximum allowable operating junction temperature	347°F	175°C
-Operating junction to case differential	20°F	11°C
Maximum allowable operating case temperature	327°F	164°C

Maximum anticipated ambient rise		90°F	50°C
-Actual operating case temperature		102°F	39°C

Maximum case temperature operating in elevated environment		192°F	89°C

The design is adequately derated, with a safety factor of 135°F (75°C) at maximum anticipated ambient temperature.

As in the technique described in the preceeding section, there will be an error in derating. Again, the error is a "safe" one and in this instance is a result of the measurement of operating case temperature. In most cases it will be smaller than the error previously described. The problem
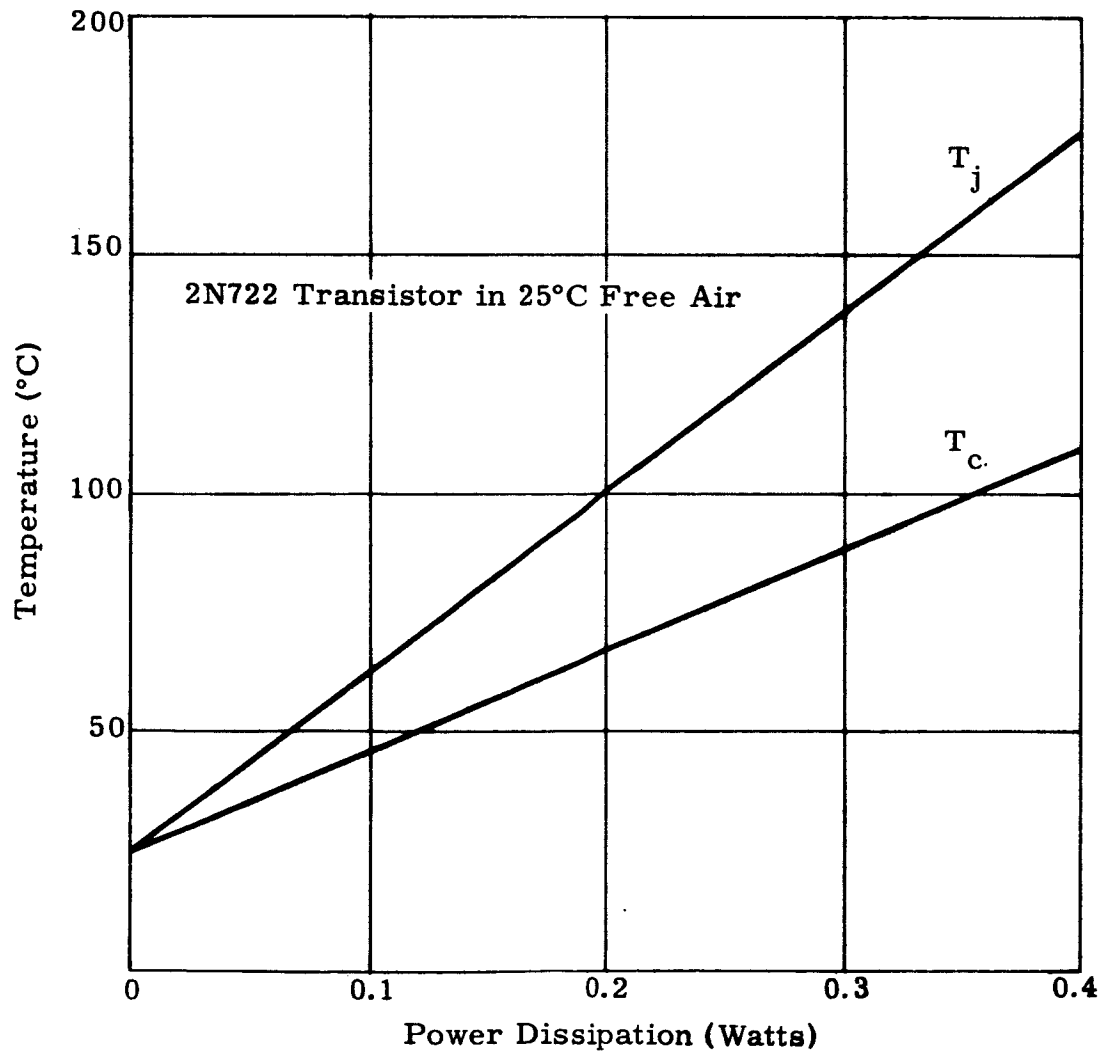
Figure 10. Operating Temperature of Transistor Q4

exists in the source of Q4's case temperature rise. Some of this increase in temperature may be due to inputs from adjacent hot components, and not from power dissipation by the transistor itself. If this is the case, the transistor is not dissipating as much as the T_C curve indicated, and the junction to case gradient is less than calculated. However, the junction to case differential was only 20°F (11°C) to begin with, and it can only go to zero. Therefore the error can be no greater than 20°F (11°C). When an adjacent component is suspected of contributing significantly to the temperature rise of the component in question, it is advisable to calculate maximum operating power dissipation from the circuit schematic and to develop the junction to case differential using the curve coordinates.

3. Troubleshooting Defective Boards Using Infrared "Fingerprints"

In this series of tests, the thermal patterns of circuit boards with defective components were studied to establish the feasibility of using infrared techniques to detect abnormalities in temperature. If such a technique could be developed, it would become a valuable troubleshooting tool, eliminating guess work and saving time and money by preventing removal of components which in reality are not defective. Initially, "fingerprints" were made exactly as in derating analysis. However, this technique did not work since temperature changes due to some defects were so small as to be virtually indistinguishable from the normal pattern. To overcome this problem, the gain of the radiometer was increased. The result of this increase can be seen in Figures 11, 12, 13, 14, and 15 where the temperature scale has been expanded.

The thermal profiles were obtained for the 18 circuits on the 6 Apollo Control Signal Processor Rate switch boards. Prior to fabrication and fingerprinting of these boards, the components were subjected to normal electrical parameter tests and met specifications. In addition, preliminary infrared measurements were made on the components.

The results of the first attempt of thermal fingerprinting are transcribed into Figure 11. The cross-hatched rectangular areas represent the normal range of temperature for each of the coded and numbered transistors, diodes, and resistors appearing on the graph. Each rectangular block, denoting minimum-maximum temperature range is the cumulative summation of 18 individual recordings of the thermal profiles for identical components of the 18 circuits. Two of the 18 circuits showed abnormal readings and these are represented by bar dots in Figure 11. These abnormalities were not known prior to recording the thermal profiles. These circuits had passed initial electrical and functional tests without showing any defects. Analysis revealed that these abnormal thermal patterns could be the result of: 1) change of power dissipation in a particular component or 2) change of thermal input from adjacent components.
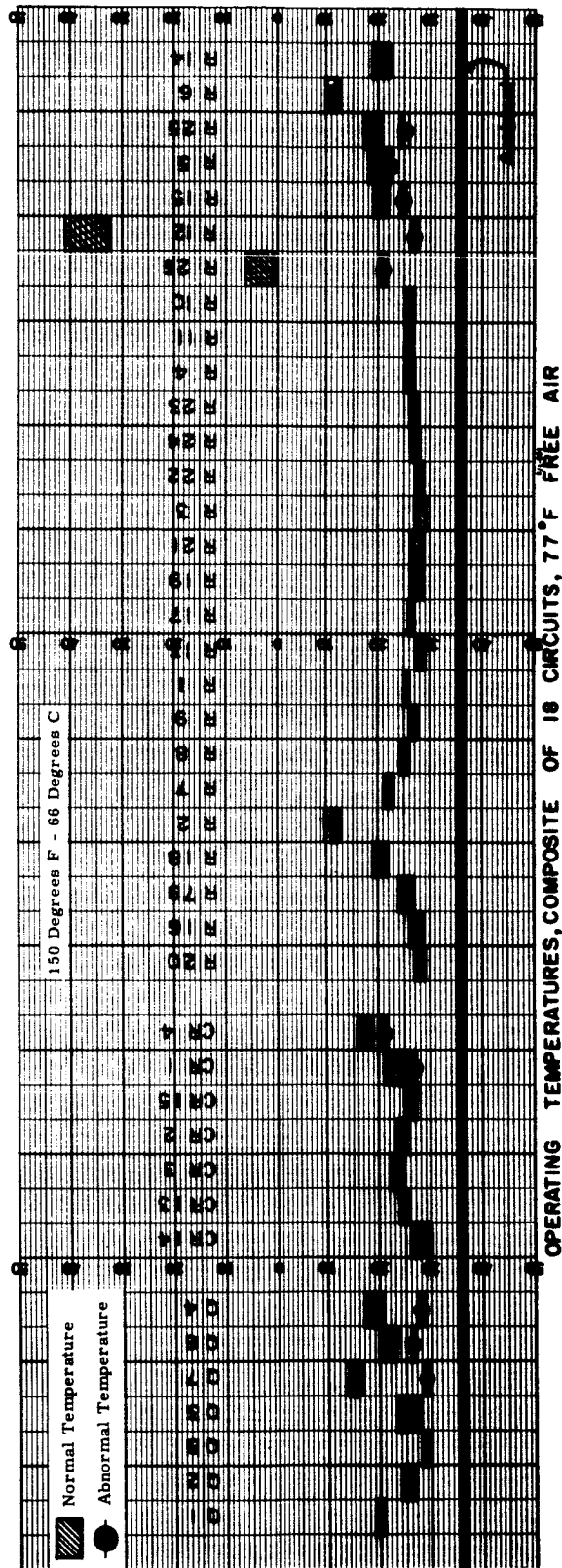
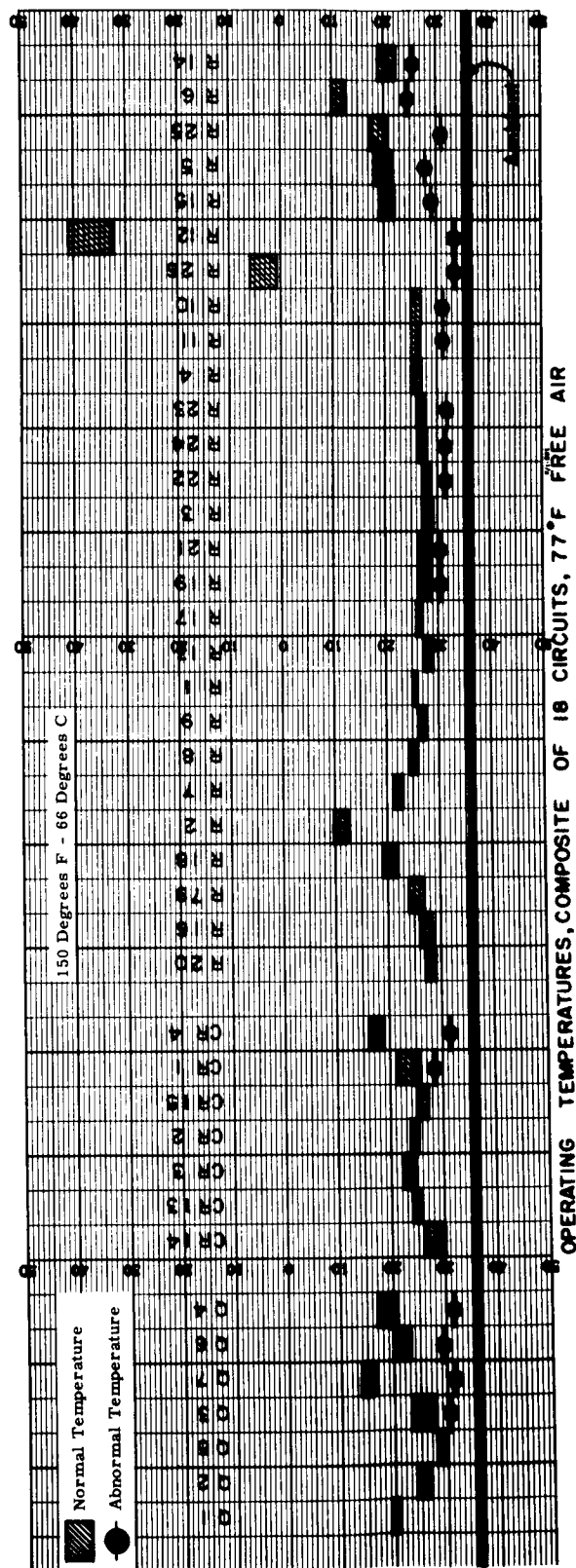Figure 11. Infrared Thermal Profile Failure of Transistor Q7

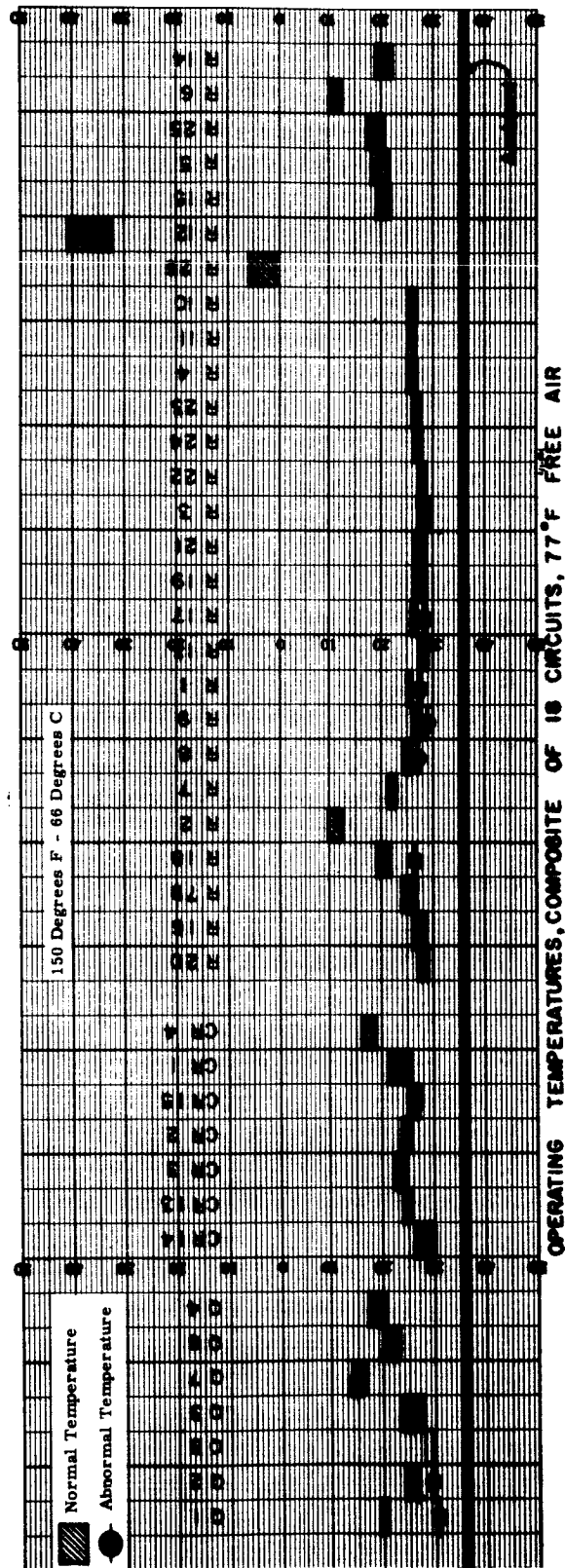Figure 12. Infrared Thermal Profile Opening of Diode CR4

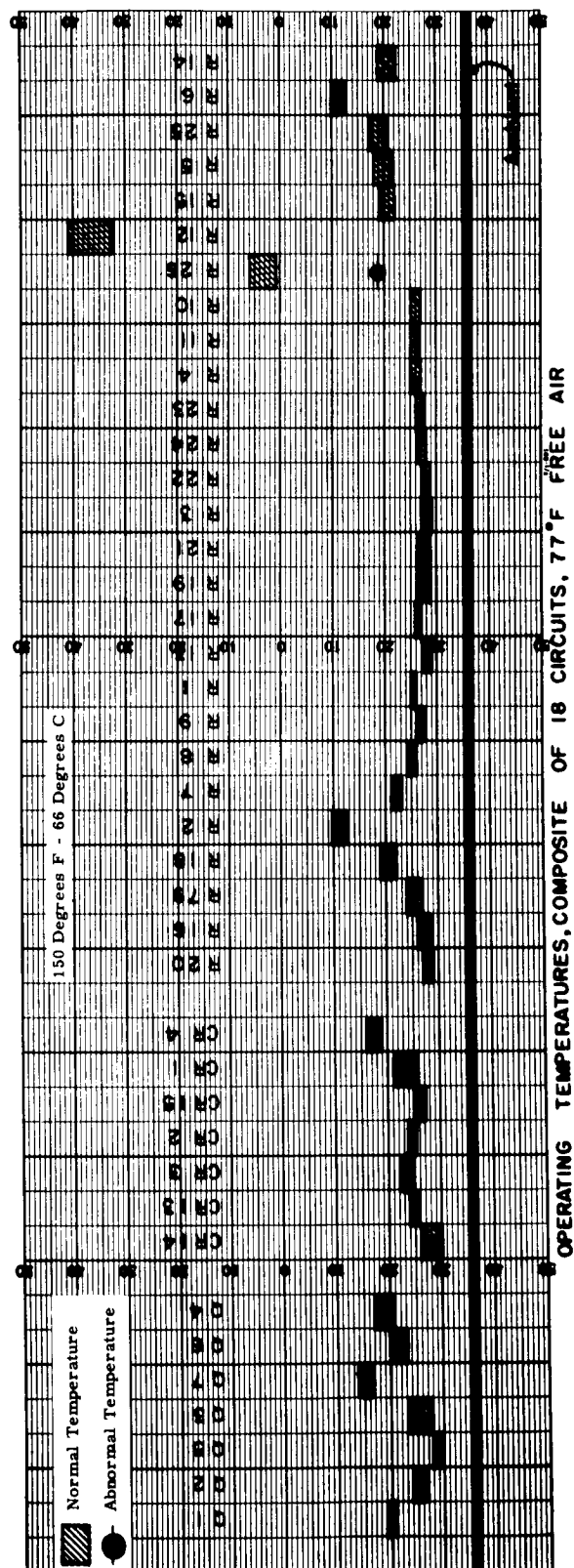Figure 13. Infrared Thermal Profile Shorting of Resistor R17

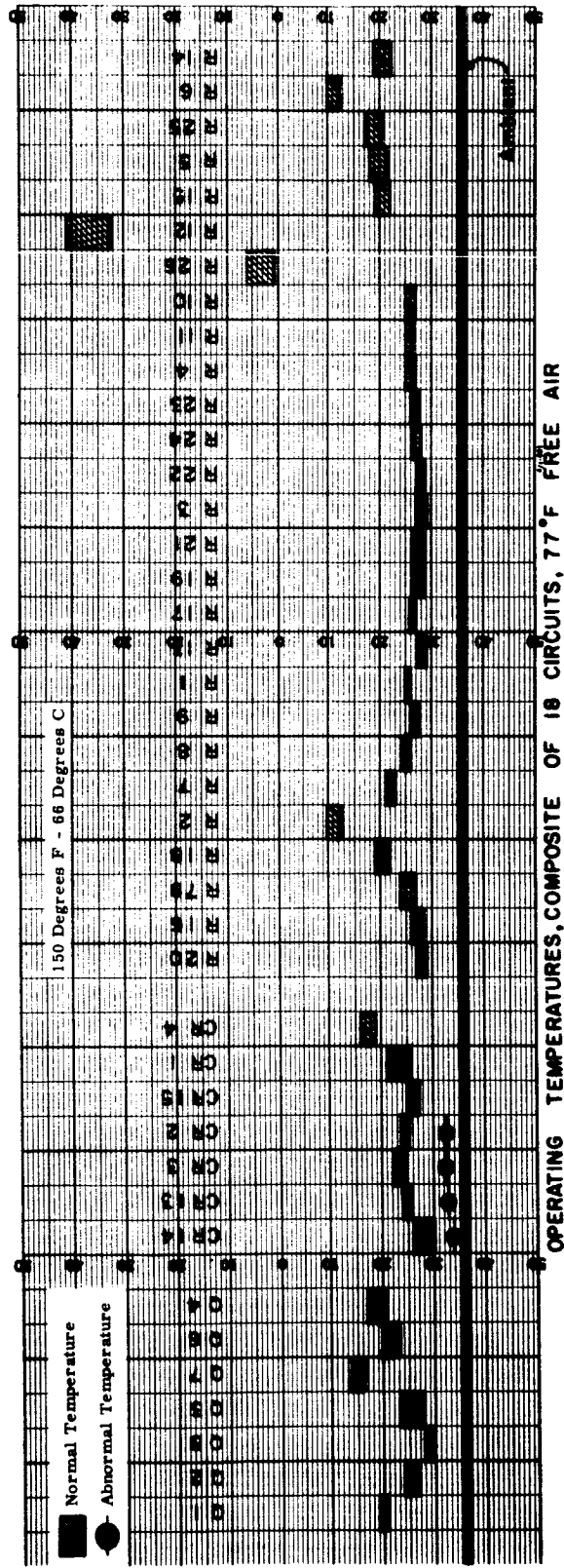Figure 14. Infrared Thermal Profile Relocation of Resistor R26

Figure 15. Infrared Thermal Profile Relocation of Diodes CR14, 13, 3 and 2.

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Conventional troubleshooting techniques were then used on one of the circuits and it was established that transistor Q7 was open. The case of Q7 was removed and the transistor examined under a microscope. The leads were melted open. A recheck of the test operation revealed that an overload had been caused when the circuit board was removed from the connector following functional test. The input connector had more than the required number of contacts, permitting 28 vdc to be applied directly to the collector of the FULL ON component Q7 during extraction. Component Q7 was then removed from the second defective circuit, its case removed, and the trouble was found to be the same.

Analysis of the schematic diagram of Figure 8 and the thermal profile show that an open failure of Q7 will reduce its temperature considerably, along with a significant drop in temperature for its base resistor R12. The temperature drops of the other components, however, cannot be explained by this circuit analysis. These temperature drops result from component layout. When the temperature of components Q7 and R12 drop, the temperature of surrounding components also drop.

To further evaluate the changes in thermal "fingerprint" due to defective components, two separate tests were performed. In the first, diode CR4 was intentionally opened and in the second, resistor R17 was intentionally shorted. Figure 12 shows the profile for open diode CR4 and Figure 13 shows the profile for shorted resistor R17. Using thermal profile, circuit diagram, and board layout information, analysis results in the same conclusion developed for the open Q7 transistor. In the case of the transistor, the defective, component produced a singularly different pattern but changes in radiation level may have been due to either the component itself or to changes in thermal input from adjacent components.

These tests show that thermal profiles can be used as a defect location technique. "Defect location" appears to be a more suitable term than "troubleshooting" for reasons which become apparent in the following general procedure for using this technique on a production basis.

Since it has been shown that a particular defect produces its own peculiar thermal pattern, and since analysis is difficult on the basis of pattern data alone, the following 4-point procedure is recommended for defect location in production testing.

1 Establish a standard thermal profile for each printed circuit board.

2 Troubleshoot the first defective board by conventional techniques and catalog the profile for any defects.

<u>3</u> Compare all subsequent abnormal profiles with this profile. If they are alike, the defect is known and no troubleshooting is necessary. If they are different, repeat the conventional troubleshooting and catalog the new defect.

<u>4</u> Repeat steps <u>2</u> and <u>3</u> on all other defective boards.

The practicality of this approach may be realized by recalling the 2 unintentional defects encountered at the outset of the tests. In the second occurrence, no troubleshooting of any kind was necessary. Only a comparison of profiles and replacement of the defective transistor Q7 was required. The 4-point procedure makes no attempt to intentionally produce any defect. Those that never occur are of no concern, while those that do occur require only a single troubleshooting effort. The difficult and expense of producing each possible defect and isolating its profile has been avoided.

C. SUBTASK 3 - THERMAL DESIGN IN PACKAGING

The 3 areas of investigation under this subtask were: 1) adjacent heating effects due to component density on circuit boards, 2) component mounting on heat sinks, and 3) existence of a thermal "walkaway" point for power transistors. The walkaway point is the point where temperature increase begins.

1. Heating Effects of Adjacent Components

In addition to the observations of adjacent component heating effects during the troubleshooting investigation on subtask 2, special experiments were conducted during subtask 3 to further investigate the effect of a component's heat on adjacent components. In these experiments, components whose temperature rise was largely due to adjacent sources were relocated. Since board layout was fixed and quite congested with the circuits available, relocation was limited to elevating the selected components well above the surface of the board. Figure 15 shows the change in thermal profile resulting from relocating diodes CR2, CR3, CR13, and CR14 by elevating them simultaneously. Figure 14 shows the results of elevating resistor R26. In both cases, the temperature of the components was reduced. In the case of resistor R26 the reduction was considerable because of the significant thermal inputs it had received from transistor Q7 and resistor R12. The change of component location was not necessary on these boards because these components were operating well below their maximum allowable temperatures. However, relocation might have been necessary had the board not been well designed and laid out. It is apparent that thermal profiles may be used to locate the hotter components on a board and evaluate the effects of their relocation.

2. Component Mounting on Heat Sinks

One object of these tests was to demonstrate the ease and accuracy with which heat sink effectiveness could be measured. This can be quite important to the design engineer when the heat sinks available are of unusual materials or shapes and are connected to other thermal conduits. For purposes of these experiments, however, various sizes of the same basic heat sink configuration were used to illustrate the point. Figure 16 shows a typical heat sink with cooling fins removed one by one. Ordinarily, published thermal efficiency data is available for the initial full configuration, but not for the changed heat sink configuration. The device in the lower left of the photograph is a specially constructed fixture which provides a three point free air suspension for the transistor and which is used to obtain thermal profile. Figure 17 shows the data from the experiments. As expected, temperature rises linearly with dissipation, and only one data point is necessary to evaluate any configuration.

Data on specific mountings is considered to be of little value in experiments such as these, since actual applications would seldom duplicate them. Therefore, absolute values were not attached to several other experiments. However it has been proven in other infrared studies at Martin-Orlando that infrared techniques can quickly, simply, and accurately provide data for evaluation of different heat sink compounds, insulating washer thicknesses, and torques applied to mounting nuts on power transistors.
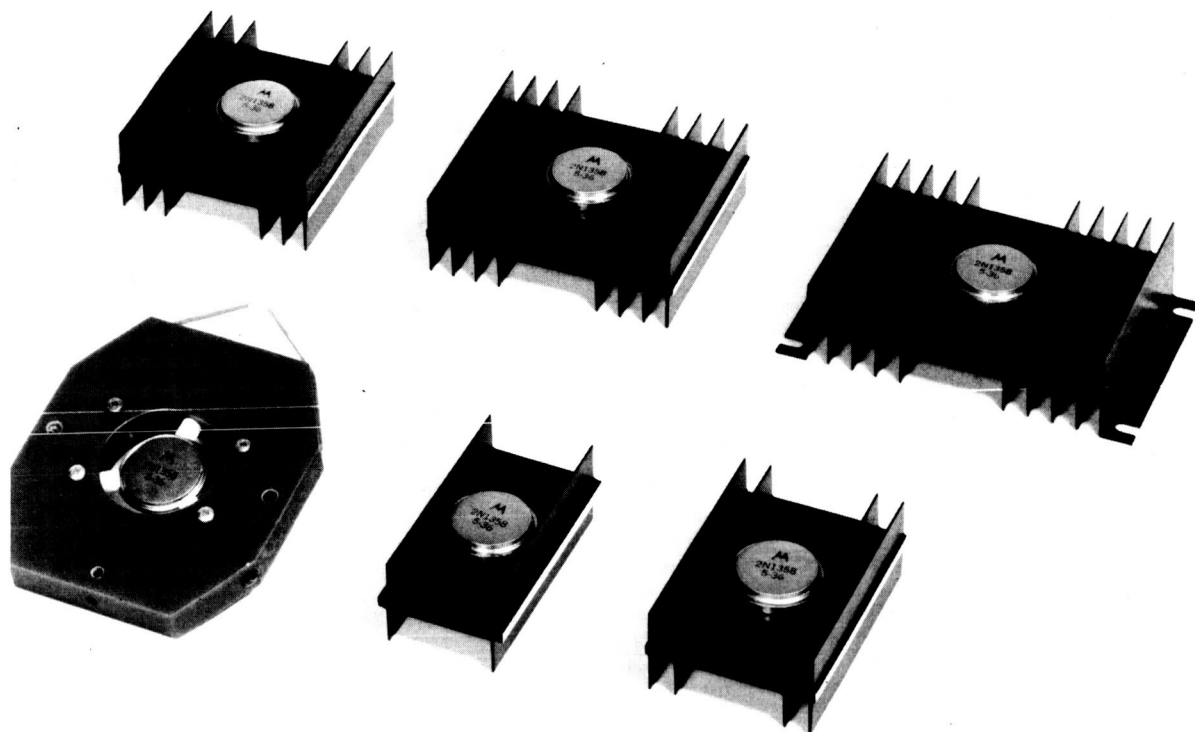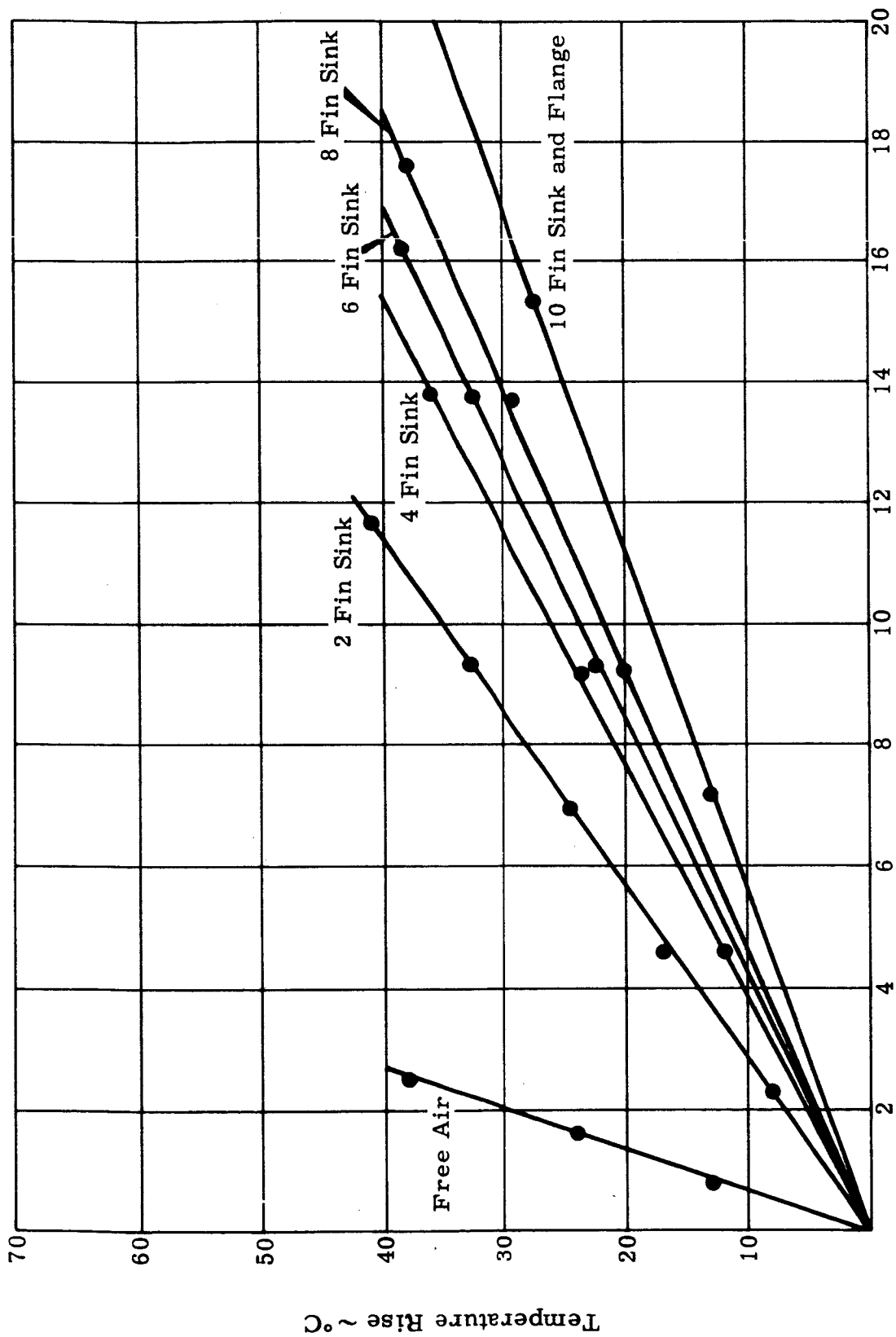
Figure 16. Experimental Heat Sink Configurations

Transistor Power Dissipation ~ watts

Figure 17. Heat Sink Efficiency

3. Thermal Walkaway

The object of these tests was to determine whether infrared techniques could be used to indicate when thermal runaway was beginning in a power transistor application; and whether or not this gradual beginning, or walk-away always occured at the same temperature. If this were the case, the engineer would have another tool for evaluation of heat sinks in high power applications. To eliminate as many variables as possible, all tests were performed with the transistor in its three point free air mounting. Figure 18 shows the circuit used for all tests.

I_c Meter - John Fluke 801

V_{ce} Meter - Triplett 630NA

R_E - Value Varies With Nature of Test
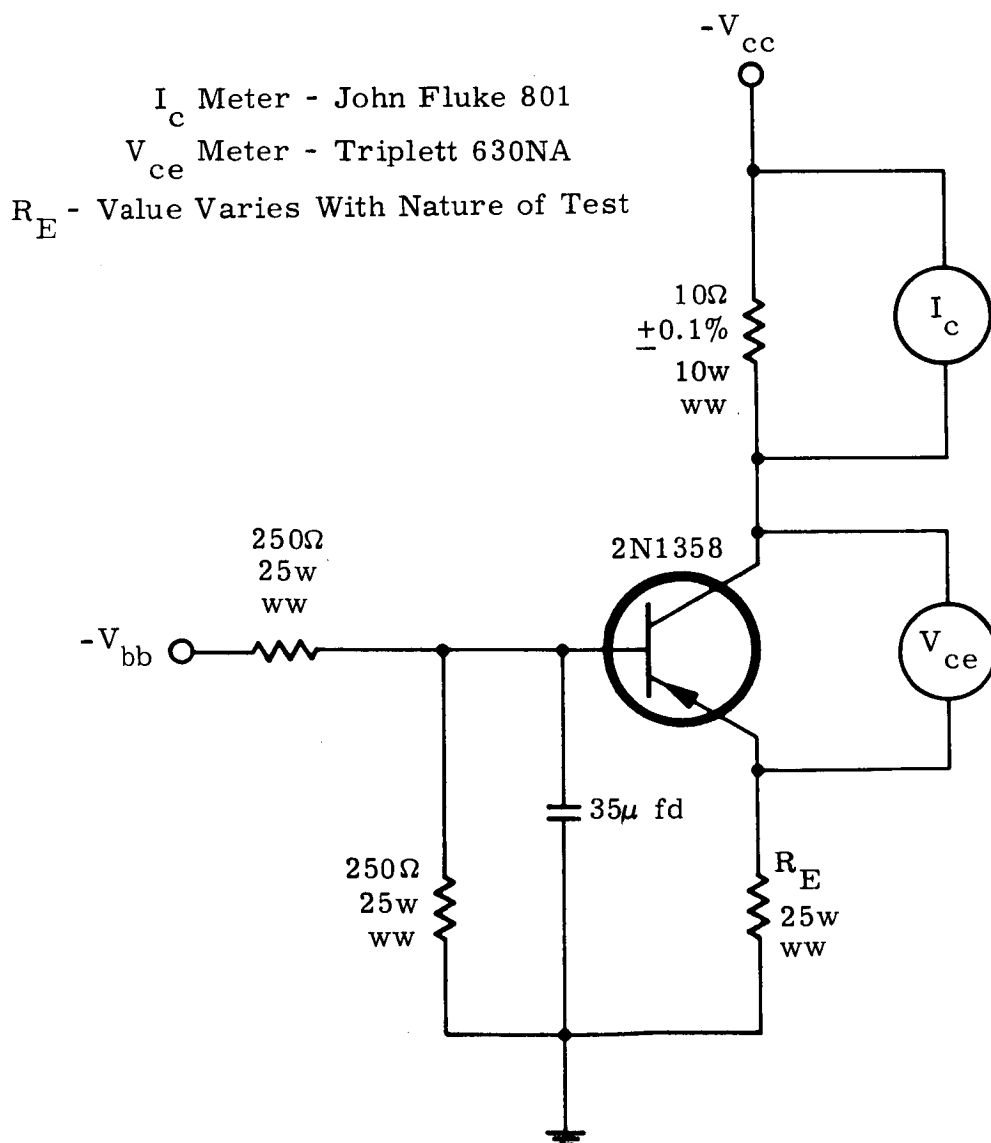
Figure 18. Test Circuit for Power Transistors

Figures 19, 20, and 21 are copies of actual strip chart recordings of these tests. The Y axis of each chart covers temperatures from approximately 65°F to 275°F (21°C to 135°C), while the X axis is the time axis at 15 minutes per major division. Each curve shows the case temperature rise of the transistor following turn on at a specific power dissipation. The terminal values of collector current (I_c) and collector to emitter voltage (V_{CE}), and hence power dissipation (P_D), vary from the initial values somewhat because of such factors as increasing leakage and gain occuring during the test. No adjustments were made to the base and collector power supplies (V_{BB} and V_{CC}) once the transistor was turned on; accounting for the drop in V_{CE} as I_C increased. The conditions of test for each curve are shown included directly below the curve.

The test results rule out the use of infrared measurement as a means for detecting impending runaway conditions in power transistor circuits. Circuit factors play a significant role in the phenomenon of thermal runaway so that infrared measurements can tell us very little, if anything, more than what the case temperature of the transistor is at any given time. Examination of the three curves in Figures 19, 20, and 21 will uphold this point by revealing the significant change in walkaway or runaway when the transistor's emitter resistor (R_E) was changed from 25 ohms to 60 ohms to 100 ohms. Note that when R_E = 25 ohms, runaway occurs at low power input and relatively low case temperature. Runaway occurs at the point at which regeneration causes an upward inflection in the curve of temperature rise. However, when R_E = 60 ohms, runaway occurs at higher power input and a higher case temperature. Then when R_E = 100 ohms, runaway does not occur, even with significantly increased power dissipation and temperature rise. Thus, there is a condition which may be called thermal walkaway because of the extended time before temperature begins to increase rapidly. This regeneration may occur over a wide range of temperatures for the same transistor due to circuit characteristics. Simply measuring the infrared radiation of the transistor will be of no value in predicting an ultimate runaway situation.

D. SUBTASK 4 - EQUIPMENT SPECIFICATIONS

The purpose of this subtask was to provide guidelines for the prospective purchaser or designer of equipment to develop a specification for an infrared radiometer tailored to a specific requirement. The experience of Martin and others in the field has shown that a single specification may be inappropriate for some specialized applications. Performance characteristics are individually listed below; and include a description of the Martin radiometer and points for general consideration when developing a specification.
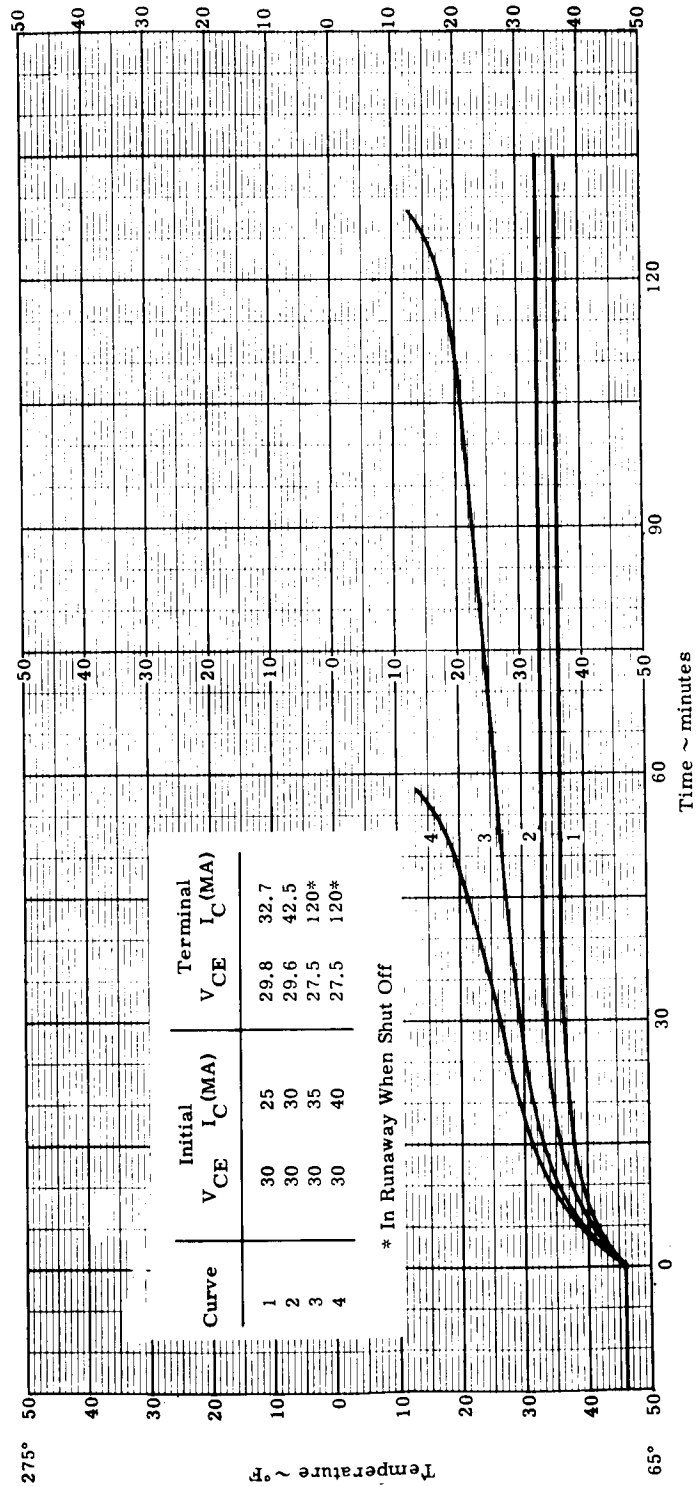
Curve	Initial V_{CE}	I_C(MA)	Terminal V_{CE}	I_C(MA)
1	30	25	29.8	32.7
2	30	30	29.6	42.5
3	30	35	27.5	120*
4	30	40	27.5	120*

* In Runaway When Shut Off
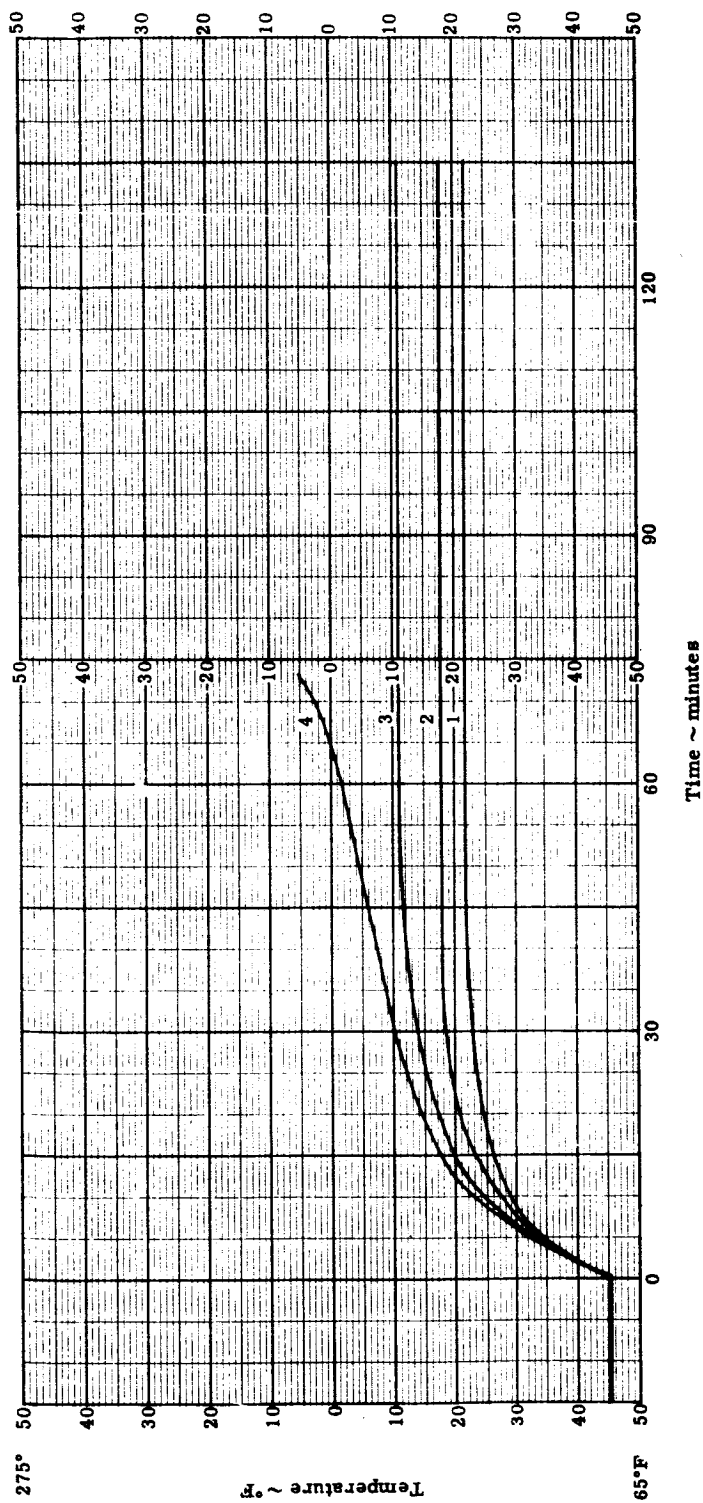
Figure 19. Temperature Rise of 2N1358 Transistor (R_E = 25 ohms)

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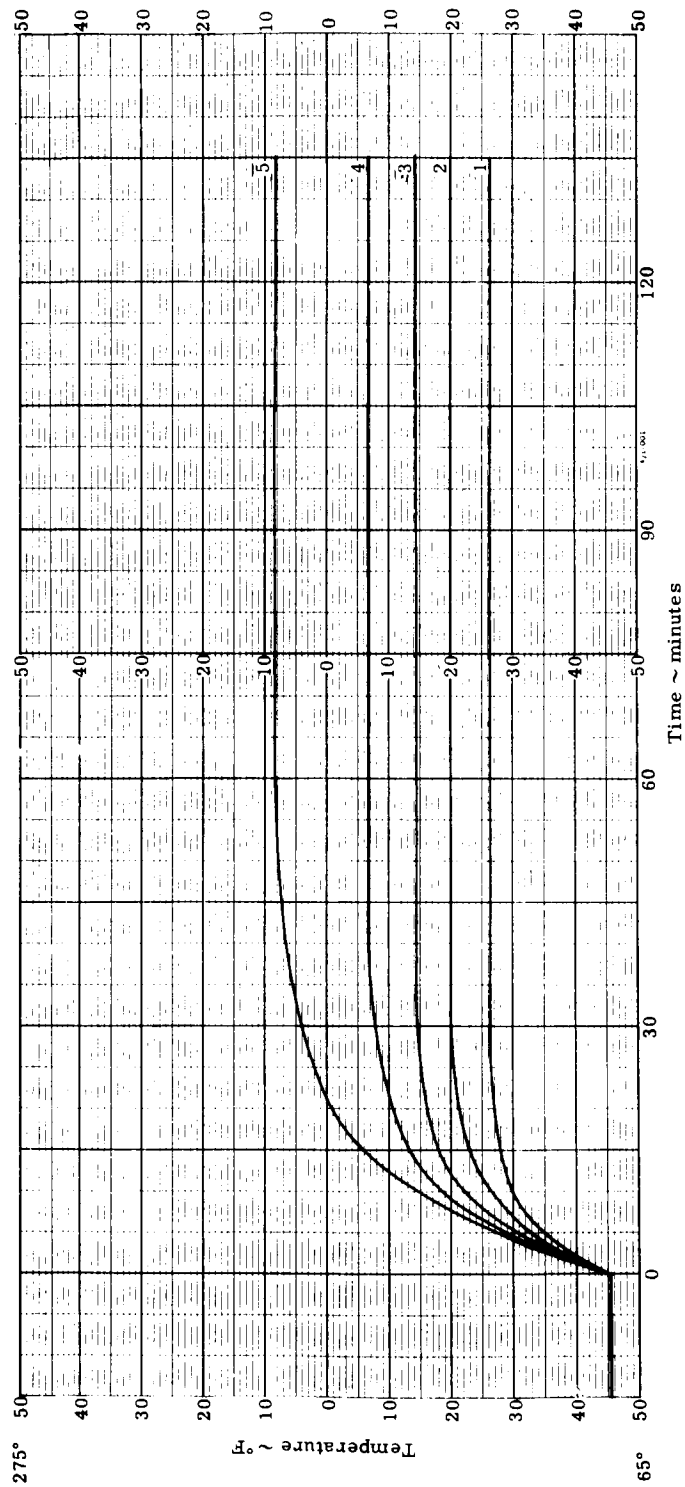Figure 20. Temperature Rise of 2N1358 Transistor (R_E = 60 ohms)

Curve	Initial		Terminal	
	V_{CE}	I_C(MA)	V_{CE}	I_C(MA)
1	30	55	29.0	73.4
2	30	60	28.5	88.8
3	30	65	27.5	110.2
4	30	70	24.8	165*

*In Runaway When Shut Off

Temperature ~ °F

Time ~ minutes

Curve	Initial		Terminal	
	V_{CE}	I_C(MA)	V_{CE}	I_C(MA)
1	30	55	29.3	64.7
2	30	65	28.9	88.2
3	30	75	28.0	103.6
4	30	85	26.6	131.0
5	30	95	22.4	203.0

Figure 21. Temperature Rise of 2N1358 Transistor (R_E = 100 ohms)

1. Performance Characteristics

   a. Field of View

   Martin System – The field of view is 0.040 inch at a minimum focusing distance of 39 inches.

   General Considerations – For practical purposes, the diameter of the field of view should not exceed one half of the minimum dimension of the component whose temperature is to be measured.

   b. Focusing

   Martin System – Focusing was accomplished by a light spot projected through the radiometer's optical system.

   General Considerations – The light spot must precisely indicate the detector's field of view, be bright enough for use under normal ambient lighting, and should cause no temperature measurement error when left on for extended periods. Sight focusing through the radiometer optics has the disadvantage of precluding focusing by the operator, who is positioned in front of the radiometer.

   c. Electronic Offset

   Martin System – This is a variable, operator controlled input signal capable of canceling average radiation levels (producing suppressed or elevated zeroes) for expanded temperature scale operation. This feature was not used on any tests of this program. It was used, however, for periodic linearity checks on the radiometer.

   General Considerations – Stability and noise are of utmost importance if electronic offset is to be used during temperature measurements, since any fluctuation of this signal will appear as a temperature change. The specifications on the Martin unit are: Stability and noise combined no worse than 0.25 percent of setting, resolution of setting no worse than 0.05 percent of range, and linearity no worse than 0.25 percent.

   d. Ambient Operating Temperature

   Martin System – The operating range is 25°C ± 5°C.

   General Considerations – Since the ambient laboratory temperature must be reasonably controlled around 25°C to best employ the manufacturers specifications, it is only necessary to assure that fluctuations of the environment will not produce temperature measurement errors.

e. Measurement Parameters

Martin System – Satisfactory performance of the radiometer used for these tests was assured by preparing specifications for such parts as the detector, internal reference cavity, and amplifier. These figures are not given as a guide because a simpler type of specification will provide the same end results.

General Considerations – Since the ultimate objective is accurate measurement of temperature, only the accuracy, resolution, and stability required need be specified. Temperature tolerances of $\pm2°C$, $\pm0.5°C$, and $\pm0.25°C$ respectively would provide excellent performance on the type of tests conducted in this program. The range of temperatures to be measured depends on the investigation. Ambient to 200°C would have sufficed for this program. In obtaining expanded scale operation without the use of offset, the internal reference cavity must be adjustable. A range from 10°C above ambient to 100°C was found to be satisfactory, since expanded scale operation was never used at high test specimen temperatures.

f. Amplifier

Martin System – The amplifier output has a maximum impedance of 1000 ohms, useable with either balanced or unbalanced recorder input and capable of $\pm2.5V$ minimum output at full scale.

General Considerations – This parameter is directly related to the type of recorder used and should be specified accordingly. A wide chart recorder capable of being zeroed at center scale is recommended. If synchronized scanning/recording is to be performed, an X-Y recorder should be used. For indexing to a position and recording, as was done in this program, a strip chart recorder with manual chart advance is useful.

2. Scanning Techniques

Thus far, no mention has been made of using area scanning techniques. The performance characteristics previously described are all related to staring techniques where the tests require: 1) monitoring a single point from T_O to an event occurrence such as in the thermal runaway test or 2) indexing to a point and making a measurement as in thermal profile development. Should single line scanning be desired, the component can be moved through the radiometer's field of view in synchronism with an X-Y recorder. Not as cumbersome a process as it appears, these techniques have served well in all laboratory experiments to date. However, production use would establish a completely different set of requirements. Also, the area scanning techniques developed during the program rely on intensity

modulation in one form or another to present data. The ability to accurately resolve shades of gray by eye is quite doubtful.

3. Test Equipment Arrangement

The test equipment arrangement developed at Martin to facilitate the measurements made during this program is shown in simplified line form in Figure 22. At point "A," a rotatable, first surface mirror has been placed at a 45 degree angle to the radiometer's optical axis. With index points every 90 degrees of rotation, the mirror permits the operator to quickly switch the radiometer input between four targets. In the sketch, high and ambient temperature references provide a constant check of air temperature around the specimen under test and of radiometer stability. The object under test is mounted on an X-Y table with a movement range of 5 inches in either axis and a positioning accuracy of 0.0005 inch. One axis of table motion may be motor driven for scanning the length of such components as resistors and diodes. Surrounding the table and specimen under test is a plexiglass enclosure to eliminate drafts. Figure 23 shows the equipment arrangement at the operators position of the infrared test bench. The advantages over vertical positioning of the test specimen or overhead mounting of the radiometer are significant.

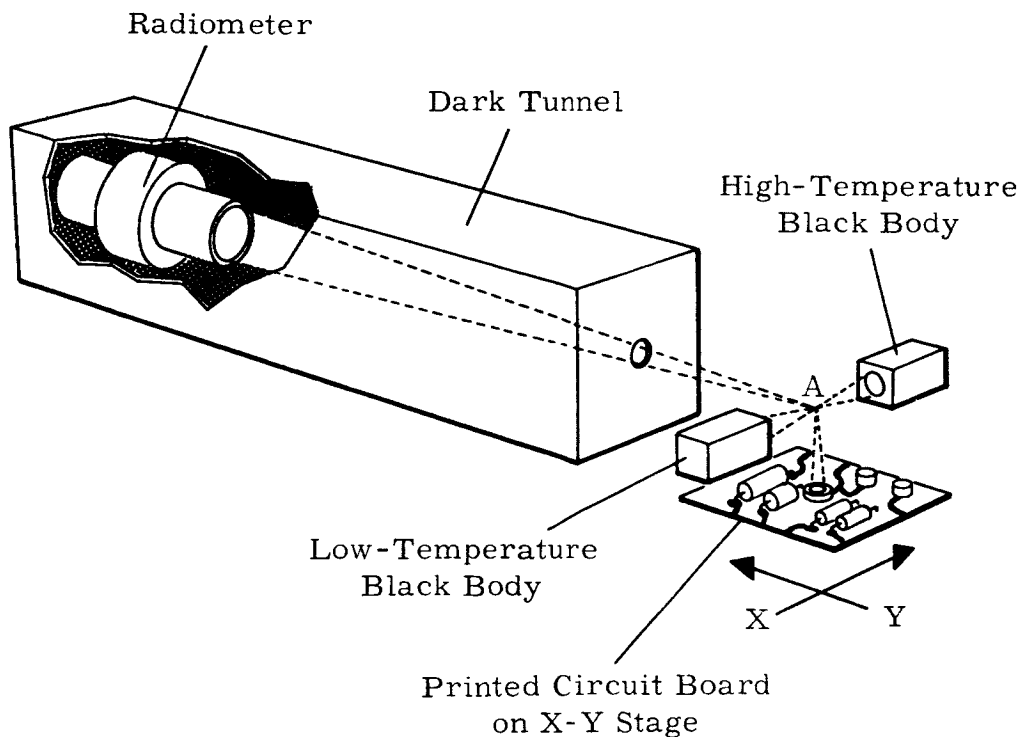A — 45-Degree, Rotating, Front Surface Mirror

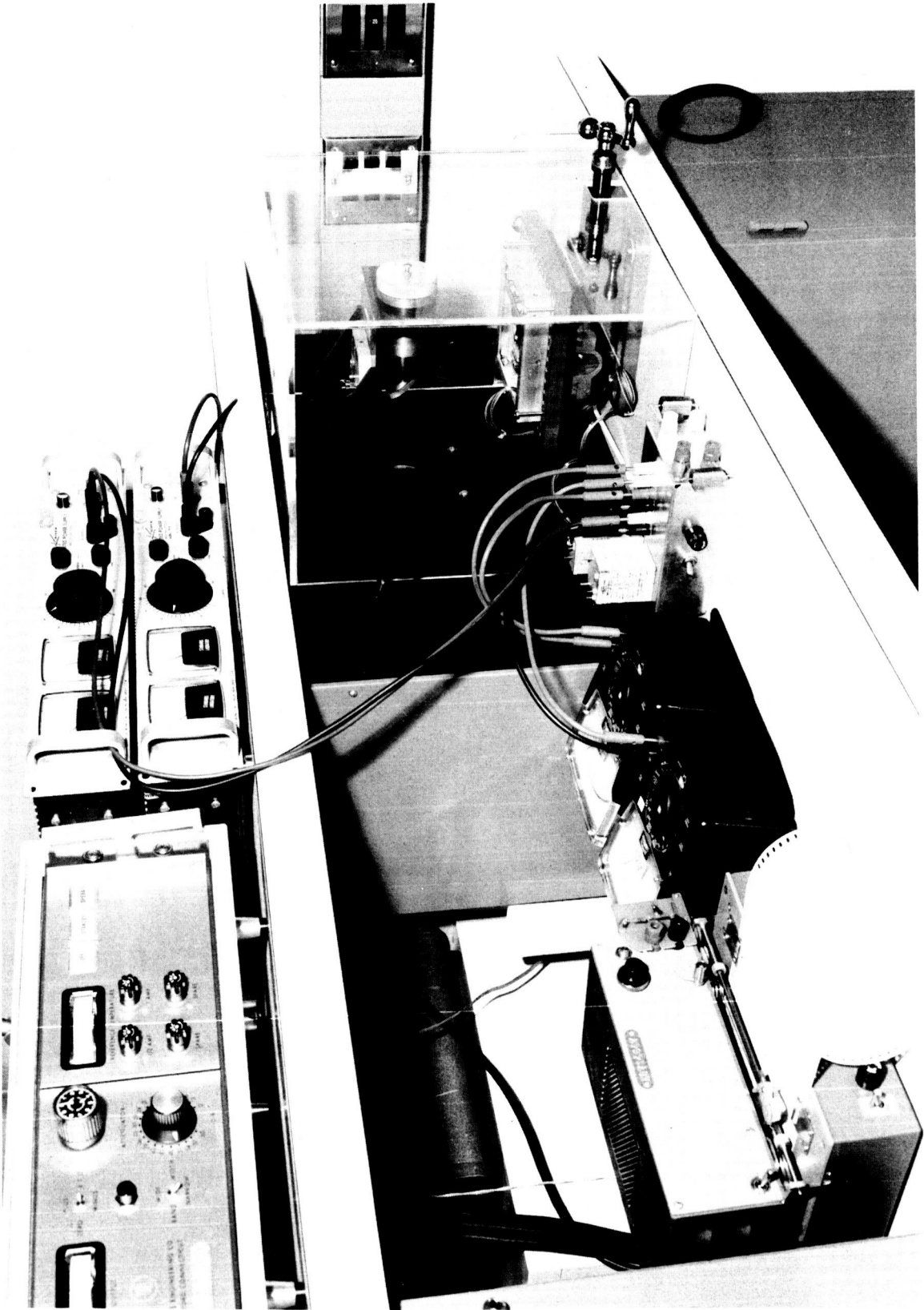Figure 22. Barnes Radiometer and Martin Designed Fixture Arrangement

Figure 23. Printed Circuit Board Scanning Arrangement

IV. CONCLUSIONS

A. PHASE I STATE-OF-THE-ART SURVEY IN INFRARED TECHNOLOGY

The conclusion drawn from the surveys is that a highly active interest exists in developing infrared techniques for electronics. There had been a phenomenal growth of investigation in less than three years, from just one or two active programs to at least 32. Two companies were producing microradiometers commercially as a direct result of this interest, and several more were under development. There were at least seven programs funded by three government agencies with more apparently planned. Furthermore, the Society for Nondestructive Testing has formed a new section devoted to infrared techniques for electronics. This action represents a merger with the originally independent Infrared Techniques for Electronics Committee.

The use of infrared techniques for application in the field of electronics appears certain since many of the studies conducted indicated a high probability of successful application. Based on reported efforts, it appears that design analysis and improvement of design techniques would be the first applications to emerge; with routine inspection among the last areas of application to be developed. For those companies involved in the design of use of microminiature circuits and subsystems, infrared appeared to be the ideal tool for precise thermal analyses and assistance in confirming difficult and complex thermal calculations.

Many of the efforts of industry were independent and many companies appeared to be going through a learning period with some duplication of effort. Additionally, many companies were working on the development of infrared techniques whose details could be considered proprietary. This situation, however, could be beneficial in the long run since, in several instances, the same areas of application were being approached from more than one direction.

Although responses indicated that all types of components were being investigated, most of the effort was directed toward semiconductor devices. Apparently, these components were considered to be a significant source of thermal problems.

Instrumentation received a marked amount of unfavorable comment with regard to its lack of adaptability for different types of investigations. There was undoubtedly a good basis for many of the complaints, but some resulted from inexperience in the acquisition and evaluation of infrared data.

Emissivity correction was consistently considered a problem. All materials in use as corrective coatings, on which details were known, were interim compounds suitable only for laboratory investigations at best. The Navy Applied Science Laboratory had investigated several commercially available coating materials which were potentially suitable for emissivity correction. At the conclusion of the Phase I survey, however, no one coating had been found which provided satisfactory emissivity correction and which would perform satisfactorily under extreme environmental conditions. No other efforts in this field were found.

The possible areas of application for infrared techniques for electronics were found to be virtually unlimited. The real problem appears to be one of sorting the potentially successful applications from the many possible applications, and then integrating these into the appropriate area. This will require considerable effort and time being spent in some very basic area of investigation such as acquiring, presenting, and interpreting the data and its variations.

B. PHASE II EMISSIVITY COATING

A study of tables presenting the test data obtained on emissivity coatings shows that most of the ten compounds tested as finalists performed satisfactorily as high emissivity, transparent, conformal coatings. In Table XXXIV, each of the compounds has been ranked according to its performance on each of the properties as determined during the test program. This table provides a ready reference and permits rapid preliminary selection of a coating to be made for use in any one of a number of environments. Final selection, however, should be made from detailed test table data since, in many instances, the variations between the first and tenth rated compound are very slight.

The only specific areas of appreciable weakness that were noted were as follows: 1) adhesion - two coatings, Minnesota Mining and Manufacturing 3M280 and humiseal 1A27, parted from the test board at relatively low value, failing at the critical coating/circuit board interface; 2) water absorption - one coating, hysol PC 22, absorbed an appreciable amount of water (1.4 percent; 3) elevated temperature electrical properties - two coatings, Martin emissivity coating and humiseal 1A27, softened excessively at the 200°F test temperature; and 4) outgassing - one coating, General Electric SS4090, a solvent containing system, outgassed to the extent of losing over 5 percent of its weight. However, in actual use as a

conformal coating, a much thinner film would be used than used for the outgassing test. This would allow a more complete escape of solvent during cure and would reduce outgassing tendencies of the coating.

C. PHASE III   FEASIBILITY OF INFRARED TESTING TECHNIQUE

1. Infrared Radiation/Life Expectancy

The infrared radiation/life expectancy correlation tests on transistors have yielded too few failures to permit other than preliminary conclusions. Six of 240 transistors placed on accelerated cyclic life test of 100, 117, 134, and 150 percent of maximum rated load have failed in less than 600 hours of ON-TIME. No additional failures have occurred during the additional 1050 hours (ON-TIME) of test. No transistor failures occurred at normal 100 percent rated electrical load during the 1650 hour test.

Due to the few failures that have occurred, this effort will be continued by Martin as an internally funded project. At present, however, it appears that although increased operating temperature does have a deleterious effect on transistor life expectancy, a significant change in temperature must take place before any effect on life can be predicted. For example, one transistor operating at 244°F (118°C) failed after 280 hours of operation, while 21 transistors operating between 276°F and 289°F (135°C and 142°C) have operated cyclically within specifications for over 1650 hours. The erratic nature of the operating life/temperature (infrared radiation) relationships seems to indicate that the manufacturer's design, production, and sorting processes may have an equal or greater bearing on life expectancy than does operating temperature. In addition, selective screening to detect potential short term failures at a receiving inspection level, based on small temperature differences, appears to be unlikely.

2. Fingerprinting and Thermal Analysis.

Infrared fingerprinting of the operating components on a printed circuit board for thermal derating analysis (determining temperature tolerances) and for troubleshooting has been proven to be feasible. The process is both simple and rapid. Although the troubleshooting techniques would have limited value in any other than volume production operations, thermal analysis can be applied with equal value regardless of the ultimate quantities to be produced.

3. Heat Sink - Infrared Measurement of Thermal Runaway

In the third subtask of this phase, the use of infrared techniques to predict thermal runaway in power transistor applications proved to be unfeasible. Other components in the transistor's circuit application, such as the

emitter resistor, exerted a much greater influence over thermal runaway than did temperature.

4. Fingerprinting - Infrared Measurement of Component Density and Component Mounting Technique

Infrared techniques were quite successfully employed in: 1) locating the hotter components on a printed circuit board and evaluating the effects of relocation and, 2) quickly and accurately evaluating a variety of heat sink configurations and transistor mounting techniques. Therefore the feasibility of using infrared in evaluating thermal designs in packaging techniques has been successfully demonstrated.

5. Equipment Specifications

Since a great variety of potential applications exist in the field of infra- red investigation, a single, specific list of required performance param- eters for instrumentation would prove inappropriate in many instances. In lieu of a specification, therefore, the necessary general performance char- acteristics were listed in Section III with a description of the radiometer used for these tests and points for consideration by the user when establish- ing requirements. These are considered adequate for laboratory type in- vestigations. For routine production use, however, data presentation and evaluation techniques must be developed to a much finer point than has been seen in any instrumentation in use thus far.

V. RECOMMENDATIONS

Based on this study the following recommendations are offered:

1. Consideration should be given to the preparation of a basic guidebook on infrared technology applicable to electrical/electronic components, subsystems, and microelectronics. This would lessen the problems created by nonstandard measurement techniques, calibration procedures, data collection and evaluation methods.

2. Consideration should be given to a study of the thermal/life expectancy relationship of a selected number of component types and sources. This study on conventional components and micro-circuits should be directed to: a) assist in establishing acceptance criteria, b) assist in determining characteristics in design affecting thermal responses and life of the devices, and c) permit the comparison of different manufacturing sources and an evaluation of their relative thermal merits as related to life expectancy.

3. Consideration should be given to a study on determining the variance in emissivity between different conformal coating lots, and determining the effect of aging in various environments on their emissivity.

4. Consideration should be given to a study of infrared as a refined technique for establishing analytical means for supplementing physics of failure studies in microelectronic devices.